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Anaerobic Digestion Assessment for Contingency Base Waste

Victor F. Medina, Scott Waisner, Steven Cosper, Giselle Rodriguez, Dominique Gilbert, Robert Tucker, Irene MacAllister, Richard Scholze, Joel Burken, and Jianwin Wang

May 2014

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Anaerobic Digestion Assessment for Contingency Base Waste

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Final report

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Abstract

A study was conducted to evaluate anaerobic digestion as a means of treating organic waste from contingency bases (CBs) and generating energy from the process through biogas. The project focused on laboratory studies to evaluate the treatment of applicable wastes and determine gas production. The study found that food waste is very effectively treated, and generates relatively large gas volumes. Methane concentrations in the gas range from 60 to 70%. Studies with latrine wastes also had high gas production, and inhibition by toilet chemicals was minimal. A pilot study was conducted at the Contingency Base Integration and Technology Evaluation Center (CBITEC) at Ft. Leonard Wood. Calculations suggest that the generated gas could offset energy use by 15 to 30%, depending on the size of the CB, and fuel cost savings (fully burdened and incorporating estimates for force protection) were estimated to be as high as $500,000 per month. Some issues were identified regarding reaction instabilities that could cause the reactors to fail. Some solutions were suggested to address these issues; one in particular uses a mix of wastes, along with food, and this mixture should improve stability and increase the utility of the process.

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Preface

The work reported herein was conducted at the US Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL) in Vicksburg, MS, and at the Construction Engineering Research Laboratory (CERL) in Champaign, IL.

Funding for this project was provided by the Leonard Wood Institute, and was managed by Joe Driskill, Executive Director. The authors appreciate the input of the Maneuver Support Center of Excellence (MSCoE) at Fort Leonard Wood, MO. This includes the assistance from COL Courtney Paul, Jim Rowan, and Ed. Lefler. Brad Pettijohn serves as ERDC Liaison Officer (LNO) to FLW, and he coordinated communications between ERDC and FLW.

Dr. Victor Medina and Scott Waisner of the EL; and Steven Cosper, Dominique Gilbert, and Giselle Rodriguez of the CERL; and Dr. Joel Burken of the Missouri University of Science and Technology (MST) prepared this report. Dr. Robert Tucker, Dr. Irene MacAllister, and Robert Scholze of CERL and Dr. Jianwin Wang of MST made important contributions to the study. In-house peer review was provided by Cynthia Banks and CPT Brent Kinney of EL. The report was also reviewed by Dr. Byung Kim of CERL and by Russell Teal of Biodico (Santa Barbara, CA), a company that focuses on biological processes and waste to energy solutions (www.biodico.com).

This study was conducted under the direct supervision of W. Andy Martin, Branch Chief, Evironmental Engineering Branch; Warren Lorentz, Division Chief, Environmental Processes and Engineering Division; and under the general supervision of Dr. Pat Deliman, Technical Director (EL).

At the time of publication of this report, Dr. Beth Fleming was Director, EL; Dr. Ilker Adiguzel was Director, CERL; COL Jeffrey R. Eckstein was Commander of ERDC, and Dr. Jeffery P. Holland was ERDC Director.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
hectares	1.0 E+04	square meters
inches	0.0254	meters
microns	1.0 E-06	meters
miles (US statute)	1,609.347	meters
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
tons (long) per cubic yard	1,328.939	kilograms per cubic meter
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

Acronyms

AD	Anaerobic Digestion
AERTA	Army Environmental Requirement Technology Assessment
BC	Base Camp
BTU	British Thermal Unit(s)
CB	Contingency Base
CCP	US Army Concept Capability Plan
CERL	Construction Engineering Research Laboratory
COD	Chemical Oxygen Demand
COL	Colonel
DFAC	Dining Facilities
DOB	Deployed Operating Base
DPW	Department of Public Works
EL	Environmental Laboratory
ERDC	Army Engineer Research and Development Center
EP,-E	Environmental Processes Division, -E Environmental Engineering Branch
EWG	Energy Working Group
FLW	Fort Leonard Wood
FOB	Forward Operating Base
FSO	Full Spectrum Operations
Ft.	Fort
FY	Federal Fiscal Year (Typically from 01 October to 30 September)
IED	improvised explosives devise
g, Kg, mg, μg	gram, kilogram, milligram, microgram
gal	gallon(s)
ISAF	International Security Assistance Force

kW, MW	kilowatt(s), megawatt(s)
L, mL	liter(s), milliliter(s)
LNO	Liaison officer
LOGCAP	Logistics Civil Augmentation Program
LWI	Leonard Wood Institute
m, mm, μm	meter, millimeter, micrometer
MCRT	Mean Cell Residence Time
MOS	Military Occupational Specialty
MSCoE	Army Maneuver Support Center of Excellence
N	normal (normality)
NATO	North Atlantic Treaty Organization
NAVFAC	The Naval Facilities Engineering Command
NPK	Nitrogen, Phosphorous, Potassium
NZW	Net Zero Waste
OACSIM	Office of the Assistant Chief of Staff for Installations Management
OD	Outer diameter
PLA	Polylactic Acid
PTFE	polytetrafluoroethylene (Teflon)
psi	pounds per square inch
rpm	revolutions per minute
sccm	standard cubic centimeters per minute
TECD	Technology Enabled Capability Demonstration
TVS	Total Volatile Solids
TS	Total Solids
UN	United Nations
UNEP	United Nations Environmental Program
US	United States
USACE	United States Army Corps of Engineers
USALIA	United States Army Logistics Innovation Agency

USDOA	United States Department of the Army
USEPA, EPA	United States Environmental Protection Agency
USN	United States Navy
VS	Volatile Solids
VS In	Influent Concentration of Volatile Solids
WWTP	Wastewater Treatment Plant

1 Introduction

Study Objective

The objective of this study is to explore the use of anaerobic digestion to treat organic waste commonly found at contingency bases (CBs). The focus of the study is to determine whether effective treatment is achieved, and to assess potential for energy generation through biogas.

Contingency Bases

Contingency bases are transitory facilities used for military and humanitarian missions. These facilities provide secure bases of operations for military missions in overseas environments. CBs are used by all the military services, but they are used most often by the Army and Marine Corps, since these two service branches — due to the nature of their missions — tend to utilize these facilities the most. Construction of these facilities is typically conducted by the military engineering units of the Army Corps of Engineers (USACE), the Naval Facilities Engineering Command (NAVFAC) of the United States Navy (USN), or by contractors (both LOGCAP (logistics civil augmentation program) and local). CBs are also used for humanitarian missions by the armed forces, the North Atlantic Treaty Organization (NATO), and the United Nations (UN). CBs can be used for disaster response, response to famine, peacekeeping missions, and other humanitarian missions.

CBs are also referred to in literature, discussions, or military documents as Forward Operating Bases (FOBs), Base Camps (BCs), or Deployed Operating Bases (DOBs), among others. In the United States Army, the following are commonly used to describe CB sizes (EWG 2012, USDOA 2013):

- Extra Small (Platoon): <50 personnel
- Small (Company): 51-250
- Medium (Battalion): 251-1250
- Large (Forward Operating Base): 1251-6000
- Extra Large (Base Camp): >6000

The Energy Working Group (EWG), a multinational task force investigating energy needs of CBs (referred to as DOBs). The EWG (2012) defined three sizes of DOBs and estimated their energy requirements (Table 1).

Table 1. Fuel and energy requirements for three sizes of DOBs.

Typical Military Organization	Task Force	Battle Group	Sub-unit
DOB Level (defined by EWG)	1	2	3
Personnel	1500 to 5000	250 to 1500	120 to 250
Daily Fuel Consumption (for electricity)	9000 to 30000 L/day 2400 to 8000 gal/day	2400 to 15000 L/day 630 to 4000 gal/day	720 to 1200 L/day 190 to 320 gal/day
Average Electrical Load (power)	1.2 to 4 MW	330 kW to 2 MW	128 kW to 270 kW

Army Net Zero

The Army Net Zero Installation Strategy was announced in 2011. The main goal of this strategy is to integrate sustainability practices at the installation level to preserve the flexibility to operate in constrained circumstances, either economical or environmental. The first step in this strategy was to select the Net Zero Installation Pilots, dividing the effort into three different categories: Net Zero Energy, Net Zero Water, and Net Zero Waste. A Net Zero Energy installation is defined as an installation that produces as much energy on site as it uses. A Net Zero Water installation limits the consumption of fresh water resources and returns the water back to the same watershed. A Net Zero Waste installation reduces, reuses, and recovers waste streams, converting them to resource value with zero landfill. Pilot installations should achieve these goals by fiscal year (FY) 2020. The Pilot installations (Table 2) were selected after an evaluation process during which several installations submitted application packages.

Table 2. Army Net Zero Pilot Installations.

Net Zero Energy	Net Zero Water	Net Zero Waste
▪ Fort Detrick, MD ▪ Fort Hunter Liggett, CA ▪ Kwajalein Atoll, Rep. of the Marshall Islands ▪ Parks Reserve Forces Training Area, CA ▪ Sierra Army Depot, CA ▪ West Point, N.Y.	▪ Aberdeen Proving Ground, MD ▪ Camp Riley, OR ▪ Fort Buchanan, PR ▪ Fort Riley, KS ▪ Joint Base Lewis-McChord, WA ▪ Tobyhanna Army Depot, PA	▪ Fort Detrick, MD ▪ Fort Hood, TX ▪ Fort Hunter Liggett, CA ▪ Fort Polk, LA ▪ Joint Base Lewis-McChord, WA ▪ US Army Garrison Grafenwoehr, Germany.
Integrated Installations (Net Zero Energy, Water, and Waste)		
▪ Fort Bliss, TX ▪ Fort Carson, CO		

Net Zero Contingency Bases

The Net Zero concept has also been applied to CBs. The Net Zero CB concept means that the CB will minimize the need to bring in energy and water, and reduce solid waste as much as practically possible. By reducing these needs, the base can operate for longer periods without the need for supplies or waste removal. The reduction of supply and waste disposal missions minimizes the exposure of soldiers and contractors to enemy action. Waste to energy (WTE) approaches assist CBs in two NZ areas: waste and energy.

Solid Waste and Wastewater Issues at Contingency Bases

Solid waste management has been identified as a massive problem during recent deployments of Army, Marine and other US, allied, and United Nations forces (Baker and Vendepeer 2004, LaRaia et al. 2012, Medina and Waisner 2011, UNEP 2010, USALIA 2013. During the Kosovo peacekeeping effort, problems were indentified with regard to the management of solid wastes in the field (Gerdes et al. 2006). Solid waste issues in Afghanistan were described in Lefler 2010. A study conducted during Force Provider Training at Fort Polk, LA found inefficient waste management as well (Ruppert 2004). Landfills could not be constructed to US standards.[1] Properly managing landfills is complicated in a combat environment, which may create local environmental impacts that have negative consequences for the native populations, defeating the concepts that are the foundation of Full Spectrum Operations (FSO). Furthermore, there have been concerns that hostile entities have obtained materials from landfills and used these materials against US soldiers, creating a force protection issue. Burning waste can be effective if properly conducted, but also can result in local air pollution. Wet wastes, particularly food waste, are not amenable to incineration without pretreatment.

Similarly, black wastewater is a challenge at CBs. A report authored by a group of military engineering experts indicates that some base camps at the time of writing still had little or no raw sewage treatment (Lefler 2010). In January 2011, Dr. Victor Medina met with Colonel F. Mendoza, Mr. Jim Rowan, Mr. Bob Danner, and Mr. Ed Lefler of the Army Engineer School and the Directorate of Environmental Integration (Maneuver Support Center of Excellence, Ft. Leonard Wood, MO). These experts

[1] Lefler, Ed. 2010. Personal Communication with Victor Medina, Directorate of Environmental Integration.

indicated that development of effective wastewater treatment for base camps is a critical need for the US Army.

Waste generation at CBs can be massive. In general, each soldier generates around two pounds of food waste each day, and each also generates a substantial amount of latrine waste. The USALIA study (2013) found that the four largest forward operating bases in Iraq and Afghanistan generated from 70 to 400 tons of solid waste per day.

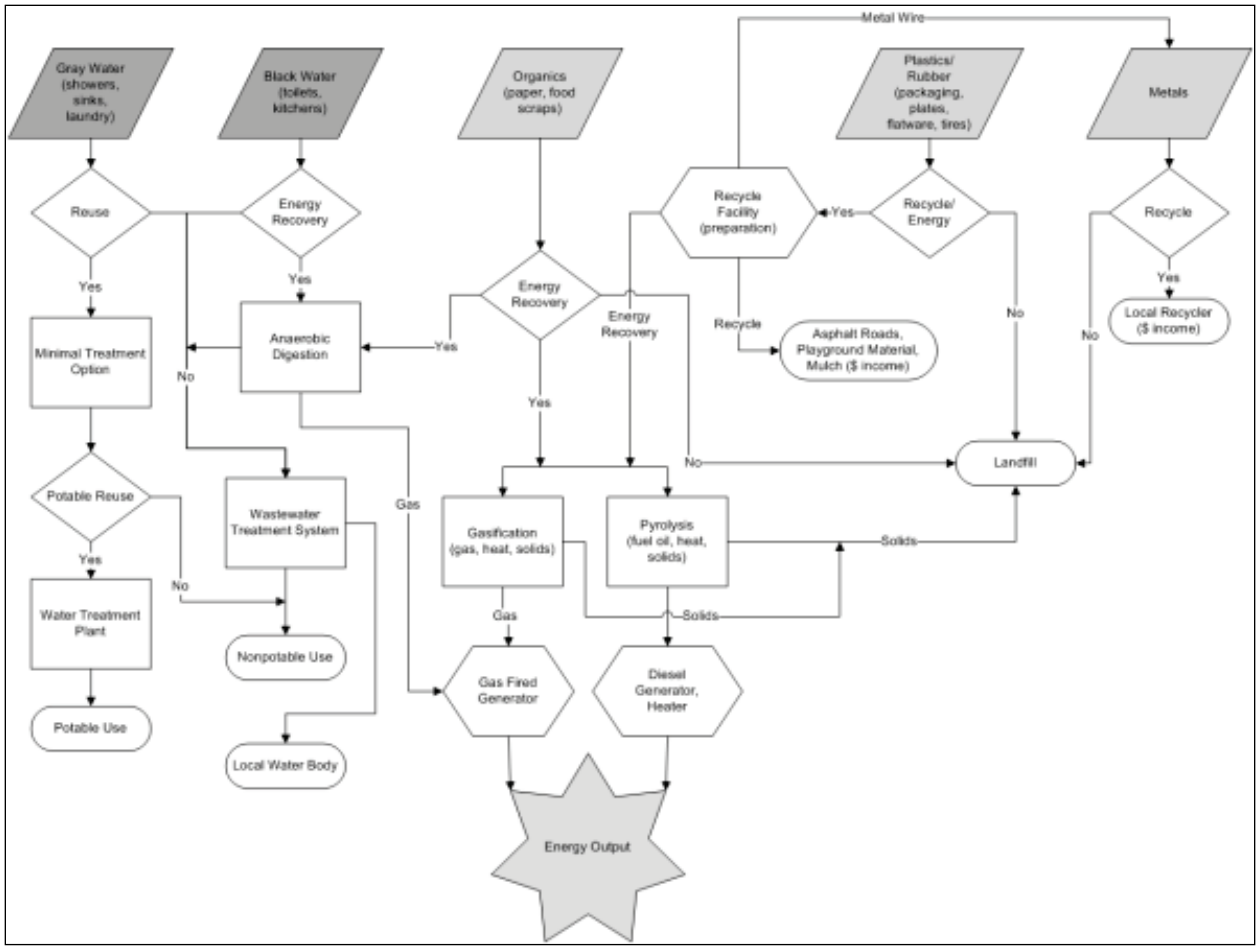
Waste to Energy Strategy for Contingency Bases

The US Army has instituted a program for Net Zero Waste (NZW) to be applied to fixed installations. Currently, this program is being demonstrated by a number of volunteer installations. The idea is to minimize — or even eliminate — all wastes currently being landfilled. The NZW program focuses first on waste reduction, then on resource recovery via reuse, repurposing, and recycling. Waste to energy is expected to be a relatively small part of the program, a resource recovery-focused strategy.

Source reduction, of course, is a logical first step in waste management for a contingency base. However, resource recovery may not make the most sense in many cases. The opportunities to reuse, recycle, or repurpose on a base are generally limited, although they should definitely be exploited whenever possible. In order to promote resource recovery, it would be necessary to engage the native population. This could be valuable in FSO, where developing the economy and infrastructure of the local area is an integral part of the mission. However, establishing the infrastructure for resource recovery with the local population takes time and energy that can detract from the mission. The process may also open possibilities for hostile penetration of the base. Therefore, a waste-to-energy focused strategy may be optimal for many contingency base operations (Medina et al. 2013).

A study by the United States Army Logistics Innovation Agency (USALIA) (2013) found that about 85% of the wastes generated in a base camp are potentially amenable to waste to energy treatments. Estimated power production from these wastes are on the order of 0.8 to 1.6 MW/day. Medina et al. (2013) indicated that waste to energy is a very sound strategy for managing wastes at FOBs, and presented a model to assess different types of waste and energy recovery options (Figure 1). This model indicates that anaerobic digestion (AD) presumably would be one of several potential means for energy recovery at a base, including gasification and pyrolysis. AD would be most effectively applied to wet waste materials (Wilson et al. 2012).

Figure 1. A waste-to-energy-focused management model developed for FOBs (Medina et al. 2013).

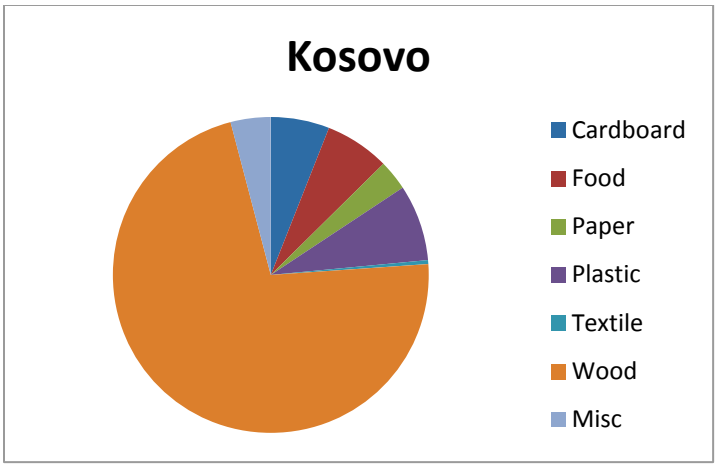


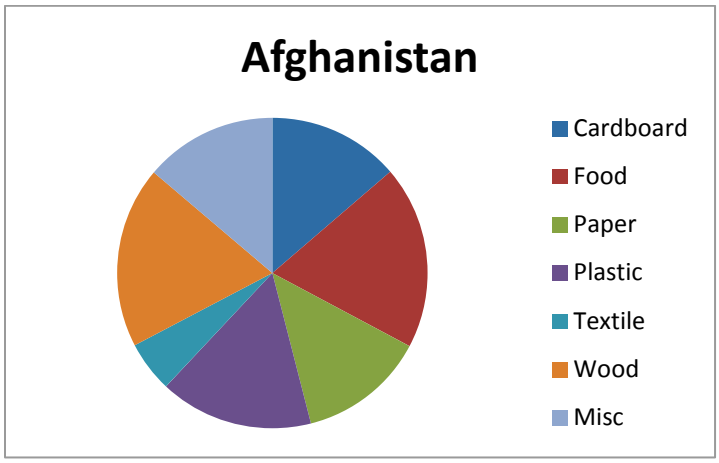
Energy from dry organic materials (paper, plastics, etc.) can be recovered using approaches like thermal waste to energy, gasification, and pyrolysis. However, these methods are not as effective for wet materials such as food, sludge, and blackwater. Anaerobic digestion is a potentially effective approach for these wet materials, providing treatment while generating methane-rich biogas that could be used directly for heating or applied in a gas fired generator (Dai et al. 2013; Zhang et al. 2013; Browne and Murphy 2013; Lim et al. 2012; Viquez et al. 2008).

Waste Characterization of Contingency Bases

Figure 2 summarizes results of three solid waste surveys conducted during recently deployed operations. Gerdes et al. (2006) conducted detailed waste surveys of forward operating bases supporting the Kosovo operations from 2003 to 2004. USALIA (2013) studied eight bases in Afghanistan and LaRaia et al. (2012) studied solid waste generated at Camp Lemmonier at Djibouti. During the Kosovo operations, scrap wood

Figure 2. Results of three CB waste surveys conducted for multiple bases in Kosovo (Gerdes et al. 2006), multiple bases in Afghanistan (USLIA 2013), and Camp Lemmonier in Djibuoti (LaRaia et al. 2012).





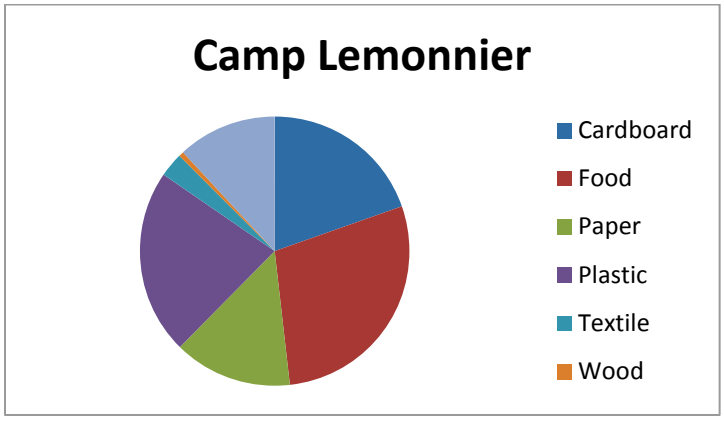


Table 3. Estimated waste generation rates for military operations developed by USAEC (2010) (adapted from Medina et al. 2011).

Component	Soldier (lbs per capita per day)	Battalion 750 capita (t a^{-1}
Generation rates on the move		
General refuse	1.5	205
Food waste	2.5	342
Total nonhazardous SW	4.0	547
Generation rates in base camps		
Plastic bottles	0.54	74
Other plastic	1.38	189
Aluminum	0.13	18
Cardboard	1.45	198
Paper	2.67	365
Food waste	1.67	229
Textiles	0.26	36
Glass	0.10	14
Scrap wood	2.95	404
Miscellaneous	2.30	315
Total solid waste	13.45[1]	1842

[1]This value is listed as 18.2 in the reference; however, the total of the values listed is 13.45.

Note: 1 lb = 0.454 kg; 1 ton = 0.907 t.

was the largest source of solid waste by weight, accounting for 72% of the wastes generated. Of the remaining wastes, food waste accounted for 6.6% of the wastes, and was the largest subsequent source of waste. In the subsequent studies conducted in Afghanistan and in Djibouti, wood waste appeared to be significantly reduced, leaving food as the greatest waste source. USACE (2008) discusses how the maturity of a CB can change the waste profile; this technical report will focus on wood. In an early camp, there may be a significant amount of construction resulting in a large amount of wood waste that decreases over time. The Balkans study included some relatively new CBs, while the Afghanistan and Djibouti CBs were generally well established, which may account for this discrepancy.

The US Army Engineer School (USAES 2010) developed waste generation numbers for planning purposes (Table 3). Once again, these estimates

indicate that food wastes are a substantial part of the wastes found in base camp settings.

Of course, mass is just one part of the story. Wood, paper, and cardboard are materials that can be readily recycled or burned for energy. They are relatively inert, and can be easily stored if needed. They can also be landfilled easily. Food waste, on the other hand, is putrescent, and can create strong and unpleasant — and for some people, noxious — odors. Food wastes are generally not recycled (Lim et al. 2012) and storing food waste while controlling odors is not easy (Browne and Murphy 2013; Lim et al. 2012). Furthermore, food waste can attract flies, rodents, and other vermin that are unpleasant and potential disease vectors. So, a strong case can be made that food is the most problematic waste generated at CBs during military operations.

Type of food waste plays a role in terms of the energy produced in an AD system. Waste that is mostly food is easier to digest than waste consisting of mixed (Browne and Murphy 2013) food and service items (napkins, plastic forks, plates, etc). Mixed materials are not impossible to use, but require more processing. The Gerdes et al. (2006) study separated out pre-consumer food (which consists almost exclusively of leftover food from the serving lines and food trimmings from preparation) from post-consumer food (which is food with other service items). The study found that pre-consumer food was about six times more in mass than post-consumer food. Latrine waste, or blackwater, is also a very unpleasant waste stream that needs to be managed, although it is generated at lower levels than food waste.

Food appears to be the largest waste material readily amenable to AD and will be the primary focus of this study. However, CB waste streams contain other wet wastes that could also be included. Larger CBs may contain wastewater treatment plants (WWTP), and the sludge from these plants could be treated by AD. At smaller CBs using cruder forms of wastewater management, the AD could accept black and grey water directly. The Gerdes et al. (2006) study found that grass clippings, which could also be used in an AD, made up 0.7% of the solid waste profile in Kosovo. It may also be possible to include a certain amount of dry organic materials (such as paper) and operate effectively (Li 2009).

Requirements

The US Army Concept Capability Plan (CCP) for Army Base Camps in Full Spectrum Operations for the Future Modular Force 2015 – 2024 calls for increased flexibility in base camp operations through sustainable and adaptable designs. Army Environmental Requirement Technology Assessment (AERTA) PP-5-06-02, Zero Footprint Camp, calls for the use of materials currently managed as solid waste and wastewater as potential resources (OACSIM 2012). AERTA MM-10-07-02 (Avoidance of Risk During Contingency Operations) specifies limiting environmental damage from military operations. This project also addresses technology gaps in Technology Enabled Capability Demonstration (TECD) 4a "Sustainable Logistics-Basing."

2 Anaerobic Digestion

Anaerobic digestion is a process during which organic wastes are degraded under certain conditions, with oxygen levels too low to allow aerobic respiration. These conditions are created by limiting the influx of oxygen while providing enough organic material to consume any residual oxygen. There is a wide range of anaerobic respiration; the goal of most anaerobic digestion processes is to produce methane (CH_4) (Nagao et al. 2012; Viquez et al. 2008).

Anaerobic digestion is commonly used in the US for biological treatment and degradation of low solids sewage sludge (under 15 percent solids) as well as for degradation of municipal, commercial, or agricultural feedstocks (Goldstein 2000). The methane generated is often used to power the waste water treatment plant (WWTP) or for heating. The use of anaerobic digestion for high solids organic waste (15 to 50 percent solids; i.e., mixed organic solids, such as food waste, manure, or green waste) is commonly practiced for energy recovery in Europe. However, its use for these waste streams is much more limited in the US.

Anaerobic Respiration

The process of respiration involves a transfer of electrons to release energy that can be used for the organism:

Electron Donor + Electron Acceptor = Energy + By Products

In general, the electron donor in the respiration process is organic matter. Different types of respiration result from different electron acceptors. In aerobic respiration, oxygen (O_2) serves as the electron acceptor. In anaerobic respiration, other elements or molecules serve as the electron acceptor. Organisms serve as biological catalysts, using their enzymes to control these reactions for their use.

Table 4 summarizes different forms of respiration commonly found in nature: the electron acceptor, products, and the energy released. In general, if a high energy reaction is available, the organisms using that reaction will have a competitive advantage over organisms that use another. Thus, when several reactions are available, the one with the most

energy will be performed first. For example, if oxygen is present, then aerobic respiration predominates. But if the environment results in a consumption of all oxygen, then anaerobic respiration can occur. If nitrate and sulfate are both available, nitrate respiration will predominate and sulfate reduction will only occur if the nitrate is consumed.

Table 4. Summary of common respiration and energy per mole of organic matter (based on Holliger et al. 2006).

Name	Electron Acceptor	Products	Energy per Electron	Comments
Aerobic Respiration	Oxygen (O_2)	CO_2, H_2O	+0.82	
Iron Reduction	Ferric iron (Fe^{3+})	Ferrous Iron (Fe^{2+})	+0.75	
Nitrate Reduction (denitrification)	Nitrate (NO_3^-)	Nitrite (NO_2^-)	+0.40	
Sulfate Reduction	Sulfate (SO_4^{2-})	Sulfide (HS^-)	-0.22	Source of foul odor in anaerobic processes
Methanogenesis (carbonate reduction)	Carbon dioxide (CO_2)	Methane (CH_4)	-0.25	
Sulfur Respiration	Sulfur (S^0)	Sulfide (HS^-)	-0.27	
Acetogenesis (carbonate reduction)	Carbon dioxide (CO_2)	Acetate ($CH_3CO_2^-$)	-0.30	Acid forming reaction

Anaerobic digestion seeks to capitalize on the methanogenic reaction. It is a relatively low energy reaction, so all the other competing reactions must be consumed first. Fortunately, in a sealed slurry reactor receiving high organic loading, consuming higher energy electron acceptors is easily accomplished. Furthermore, the continuous loading of organic material allows for stable methanogenic reactions to occur.

Acetogenic reactions, which are slightly less energetic than methanogenic, (Table 3) are necessary for methanogenesis, because they break down complex organic materials into forms that methanogens can utilize. However, acetogenic organisms also compete with methanogenic organisms, and can be problematic. If methanogenic reactions can be promoted, they can effectively work symbiotically with acetogenic reactions to generate methane. During startup, this is achieved by providing a large seed of methanogenic microorganisms. A strong bulk of these organisms can allow the reactor to develop a predominance of methanogenic activity. However, acetogenic reactions can produce acids, and these acids can poison methanganic microorganisms if they begin to predominate. This can

result in reactor failure, sometimes to the point where it is necessary to start completely over again.

Anaerobic Digestion of Food

Anaerobic digestion has been demonstrated to be very effective at treating food wastes (Nagao et al. 2012, Zhang et al. 2013). Garcia-Pena et al. (2011) demonstrated that AD was effective at degrading fruit and vegetable wastes found at a market area in Mexico City and that effective biogas production was found. The pH and some nutrients, particularly nitrate availability, were found to be particularly important in achieving peak performance. Zhang et al. (2007) also found food waste to be an excellent feedstock for the AD process. Excellent methane yield was found (348 to 435 mL/gVS after 10 and 28 days of digestion, respectively) and the average methane content of the biogas was 73%. Bernstad and Jansen (2012) studied four different approaches for separate collection of household food wastes for anaerobic digestion. Their work showed that the use of AD reduced available nutrients, thereby minimizing issues associated with eutrophication, acidophication, and greenhouse gas potential. Ike et al. (2010) studied changes in the microbial community for an AD that treated food wastes from an industrial operation. They found the microbial community changes according to the depth in the reactor and that changes in the community occurred in the 150 day startup time. *Methanosarcina* sp. and *Methanobrevibacter*/*Methobacterium* sp. eventually established themselves as the dominant methane-producing bacteria in the reactor. Vlachopoulou (2010) conducted modeling studies, comparing AD of food waste with and without the use of sewage sludge as an additive. Her simulations suggest that sewage sludge would have a beneficial effect on the anaerobic digestion of food wastes, resulting in more complete degradation, and that the process should stabilize the sludges, making them innocuous.

Service Items

Often, food waste can be mixed with service items, such as paper, and plastic products such as paper plates or plastic utensils. Biodegradable plastic (polylactic acid or PLA) items are commercially available and have been used by various installations. These items have been demonstrated to be biodegraded in composting operations and in soils (Ho et al. 1999, Hoppenheidt and Tranker 1995). The increased temperatures found in composting operations resulted in about an eight fold increase in the

degradation of these plastics. These results suggest that an anaerobic digester, which generally operates at higher temperatures than compost piles, could also be effective at degrading these materials. El Mashad, et al. (2012) found that biodegradable plastics were successfully biodegraded in an anaerobic reactor.

Fats, Oils and Grease (FOG)

Fats, oils, and grease (FOG) tend to be more difficult to degrade, and can be a potential issue in anaerobic digestion. However, controlled additions of FOG can be tolerated by AD systems and can even result in higher biogas production (Suto et al. 2006, Cockrell 2008, Kabouris et al. 2009).

Mean Cell Residence Time (MCRT)

Since anaerobic digester reactors typically employ some form of mixing to promote solids contact with water, mean cell residence time (MCRT) is typically used to describe the reaction time. The MCRTs for anaerobic digestion are typically on the order of days. For example, Gray et al. (2008) tested MCRTs ranging from 5 to 15 days for the treatment of food and municipal wastewater solids. At 5 days, the reactor produced gas that had a methane content of <5%. At 10 days, the average methane content was 59% and at 15 days the methane content further increased to 64%.

Volatile Solids Loading Rate

Gray et al. (2008) identified volatile solids' loading rate as an important design factor; the higher the loading rate, the greater the bioactivity, the higher the gas production, and the higher the methane production. However, too high of a volatile solids loading rate can cause the reactor to crash, as it can promote acid buildup and acetogenic activity.

Temperature

Anaerobic processes are generally significantly slower than aerobic respiration (Henze 2002). Generally, it is necessary to raise the temperature to at least mesophillic conditions for anaerobic reaction rates to reach reasonable levels. This is true with methanogenesis, where 35°C (mesophillic) is generally considered a reasonable level to promote effective reaction rates. With sufficient insulation, biological activity can sometimes achieve sufficient temperature increase; but in most cases, it is necessary to supply supplemental heat.

pH

Methanogens generally operate at a pH range of 6 to 8 (Henze 2002). If the pH drops below 5.5, activity is significantly hindered and can stop completely and irreversibly (requiring reseeding of the reactor).

Inhibition

According to Henze (2002), the following materials can be inhibitory at the given concentrations:

- Ammonium: >100 mg/L
- Hydrogen sulfide: >250 mg/L
- Cyanide: 5 mg/L
- Trichloromethane: 1 mg/L
- Formaldehyde: >100 mg/L
- Nickel: >200 mg/L

Biogas

Methanogenic anaerobic digestion produces biogas, which consists primarily of methane and carbon dioxide. Depending on the efficiency of the reaction, the methane content can vary from 40 to 70% (Vlachopoulou 2010). Various impurities can be found in biogas, including hydrogen sulfide, mercaptins, hydrogen, and ammonia. Many of these constituents can cause odor and corrosion issues if they become too concentrated. Feed materials can affect the prevalence of these impurities.

Deployable Anaerobic Reactors for CBs

Installing deployable waste to energy systems can be an effective approach to managing solid waste and blackwater at contingency bases. Contained reactors used for these applications allow for control of air contaminants. Additionally, as energy is a critical need for base camp operation, producing energy from waste can provide a tremendous benefit for the base camps and for military operations in general.

One deployable unit that the authors are aware of is produced by the German company, Eisenmann, and is marketed in the United States by Ciycor (New Lenox, IL, http://www.ciycor.com) (Figure 3). ERDC has determined that this reactor could be suitable for a 600-person contingency base. The EISENMANN Biogas Compact Plant is an integrated and preassembled

containerized anaerobic digester, with dimensions of approximately 12m x 2.5m x 2.5m, which can be easily integrated into a FOB. Moreover, the methane produced from this process could be incorporated into the utility systems for heat and power.

Figure 3. EISENMANN Biogas Compact Plant.

The system operates by filling solid substrates into the substrate feeding device. In this device, the substrates are mixed and fed into the digester by a screw type conveyor system. The substrate feeding device is equipped with a weight-based metering system. To avoid problems with sinking or swimming substrates, the digester is equipped with a high performance mixing system that reaches the complete volume of the digester. Also, to achieve a long retention time, the digester is divided into two separate sections. A biogas storage membrane is integrated into the container which offers a short buffer capacity during brief outages of the biogas consumer. An air injection system is included to reduce the H_2S content of the biogas. The common digestate generated from an Anaerobic Digestion system is a nutrient-enriched fertilizer product containing nitrogen, phosphate, and potassium (NPK). The digestate could also be used for a food supplement for farm animals, fertilizer for fish ponds, worm rearing media, and supplement for seed germination.

This compact, containerized all-in-one high solids anaerobic digestion system facilitates processing of a broad range of organic material. This

system can process both high and low solids (up to 45%TS). The horizontal plug flow design has a relatively high tolerance for contaminants (e.g., packaging, silverware, and other solid objects which would otherwise foul alternate technologies). This robust design is ideal for a forward operating base with varied inputs and feed rates. Although this is a system the authors are aware of, there may be other worthy systems available or systems that will be developed in the future.

Simple Anaerobic Digester Approaches

Another option to deployable reactors is to use simple approaches that have been commonly used for sanitation and waste management in Asia and South America (Lansing et al. 2007, Lansing et al. 2008a, 2008b, Lansing et al. 2010, Lansing and Moss 2010, Viquez et al. 2008). In addition to waste treatment, these treatments generate biogas that is usable for heating and cooking purposes and even electrical generation. One option is a covered lagoon system, which is a low maintenance system commonly used for agricultural operations (Figure 4). Covered lagoons are inexpensive to construct and low maintenance and could be adapted for medium to small FOBs. Another inexpensive option is the plug flow bag approach, commonly used in Asia and South America, and applicable to small FOBs. Bag reactor approaches have been developed to provide sanitation in economically challenged countries at installation costs ranging from $150 to $1,500 (Lansing and Moss 2010).

Figure 4. Two examples of simple anaerobic digester reactors: covered lagoon (left) and bag reactors (right) (from Lansing and Moss 2010).

3 Methods

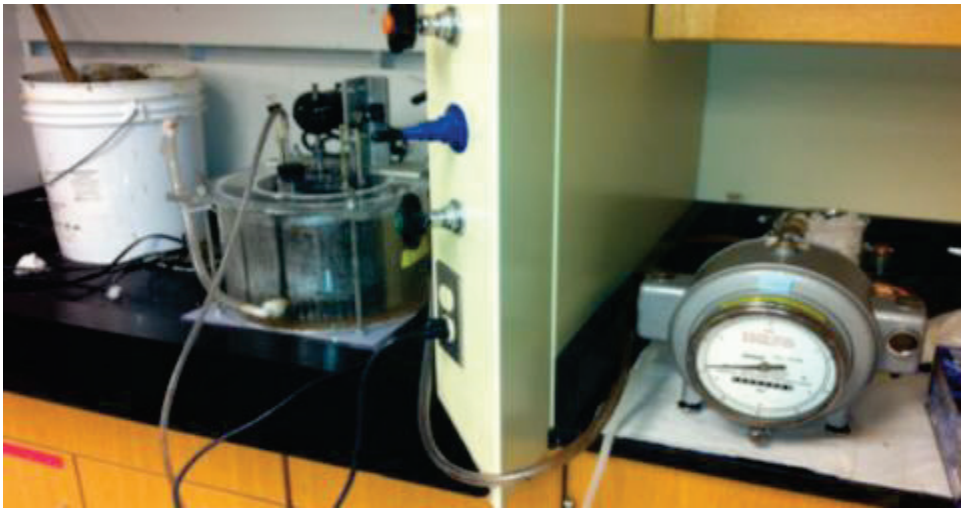
The project consisted of two laboratory experimental sets conducted in parallel. The first experimental set focused on batch, microcosm studies. In these studies, multiple (8) reactors received a substrate, and their performance was monitored over time. The multiple reactor set up allowed for comparative performance. The second study used a single, 5-liter reactor, which was operated as a semi-continuous flow, mixed reactor, and it received over multiple feedings. The 5-liter reactor study was conducted at the Army Engineer Research and Development Center (ERDC) in Vicksburg, MS. A pilot scale field reactor was then prepared and studied during a short demonstration at the Contingency Base Integration and Technology Evaluation Center (CBITEC) at Ft. Leonard Wood (FLW), MO.

Anaerobic Microcosm Study (conducted by MST)

"Mother" Reactor

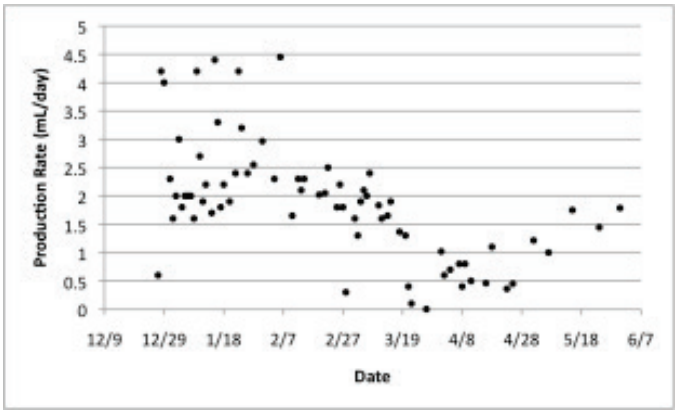
A 5-liter biogas anaerobic reactor was utilized to develop an anaerobic consortium for the project (Figure 5). The reactor was seeded with solids from the wastewater treatment plant at FLW. The reactor biomass acclimated to the increasing feed concentration to 20 g/L/day. Once the steady state gas production rate was reached, this biological culture in the "mother" reactor served as the standard seed for the waste-specific biogas production studies.

Figure 5. The "mother" reactor (to the left) and the gas flow gauge (right) used for the microcosm experiments.



The project was conducted from early December 2012 to early June 2013. The mother reactor was initially fed swine waste, which was obtained from a hog farm near Vienna, MO. In late December, the reactor substrate was changed to include food waste. In early March, the primary substrate was changed to waste-activated sludge gathered from the secondary clarifier at Rolla's Southeast Wastewater Treatment Facility. The gas flow from the mother reactor was measured periodically throughout the testing period (Figure 6).

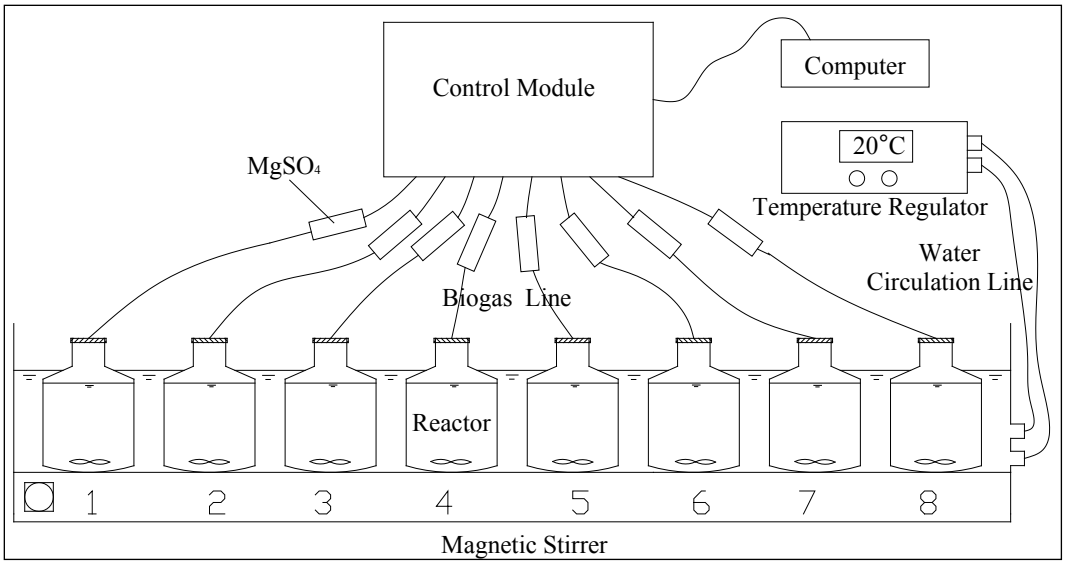
Figure 6. Biogas production of the mother reactor, operated from December 2012 to June 2013.



Respirometer Reactor System

A pulse-flow PF-8000 aerobic/anaerobic respirometer (Respirometer Systems and Applications, Fayetteville, Arkansas, USA) was used to test the waste biogas production (Figure 7). The system consisted of a control module, eight bioreactors in a water bath, and a computer. A scrubber containing magnesium sulfate ($MgSO_4$) was used to remove the moisture in the biogas which might damage the control module. This setup was used for multiple experimental sets, two of which will be discussed in the report. The first focused on the degradation of food, comparing it to digestion of wastewater treatment sludge. The second set studied digestion of blackwater collected from portajohns at FLW. It studied the effect of disinfection chemicals by comparing raw material (with these chemicals) and rinsed material (with disinfection chemicals removed by rinsing).

Figure 7. Anaerobic digestion respirometry system used in the microcosm study.



Experimental Details

Food Waste Tests

A total of four batch tests were completed using primary sludge and mess hall food waste as substrate. Batch tests one and two, which used food waste and primary sludge as substrate, were run from 21 November through 28 November 2012 and 28 November 2012 through 7 December 2012, respectively. Tables 5 and 6 summarize operating conditions of these tests.

Table 5. First batch test parameters for food waste and primary sludge (21-28 November 2012).

Re-set up the batch test for food waste and primary sludge								
Reactor		seed (mL)	Waste	g-TVS	Water	Total	K2HPO4	
1	Food	160	100 mL	10	140	500		
2		160		10	140			
3		160		10	140			
4	Primary sludge	160	340 mL	10	0			
5		160		10	0			
6		160		10	0			
7	Control-1	160	0	0	340			
8	Control-2	160		0	340			

Table 6. Second batch test parameters for food waste and primary sludge (28 November – 7 December 2012).

Second batch test for food waste and primary sludge								
Reactor		seed (mL)	Waste	g-TVS	Water	Total	K2HPO4	Initial pH
1	Food	120	75 mL	7.54	175	370	5g	7.5
2		120		7.54	175	370	5g	7.5
3		120		7.54	175	370	5g	7.5
4	Primary sludge	120	250 mL	7.34	0	370	3g	7.3
5		120		7.34	0	370	3g	7.3
6		120		7.34	0	370	3g	7.3
7	Control-1	120	0	0	250	370	1g	7.2
8	Control-2	120		0	250	370	1g	7.2

The third batch test was run from 7-17 January 2013. In this test, reactor feeding was reduced to 3 g-TVSS food or primary sludge. Before adding the waste to the culture, the pH was increased to 9. Additionally, 2 g K_2HPO_4 was added to each reactor. Gas production of the seed culture was approximately 2.2 mL/day at the time it was removed from the mother reactor.

The fourth batch test for using food waste and primary sludge as substrate was run from 17 to 27 January 17, 2013. In this test, 3 g-TVS of food waste or primary sludge was once again added. Gas production of the seed culture was approximately 2.8 mL/day at the time it was removed from the mother reactor. Two control reactors without waste addition were prepared.

Latrine Waste Tests

Overview

Latrine waste is characterized as human fecal waste and urine with a bacterial inhibitor commonly known as “Blue Water.” There are several types of chemical inhibitors that could be used to prevent organic anaerobic degradation from occurring in the latrine. Although formaldehyde was once preferred, suppliers are now switching to glutaraldehyde or a combination of the two. The latrine waste collected for this experiment already contained inhibitor, which presented a number of challenges to the researchers. These challenges should be considered for practical application of latrine waste as anaerobic substrate and include:

- The type (i.e., glutaraldehyde, formaldehyde, etc.) and percentage or concentration of active biocide in the Blue Water is unknown.
  - This can be addressed in a holistic operational setting.
- There are typically several latrines in use at any given time, and it is common for excreta to be unevenly distributed from latrine to latrine.
  - The contractor is likely to remove content from all latrines, regardless of use, and recharge each with approximately fifteen gallons of Blue Water.
- In this experiment, the substrate sample was taken directly from the latrine, presumably from the one most filled where excreta is easiest to reach.
  - This could result in higher gas recovery than if the sample were taken from a composite of all latrines, and if the previous presumption is true.

Acknowledging these caveats, this set of batch experiments provides a topical glimpse into potential recovery as well as future methodologies to improve recovery rate and/or efficiency.

Experiments

Test preparation began when two containers each filled with 2.5 gallons of latrine contents from Test Area 246 at Fort Leonard Wood were delivered to MS&T on Monday, February 4 2013. These containers were placed in storage at ~5°C until Tuesday, February 5.

Sample preparation began by decanting the excess "blue water" from the original sample volume (Figure 8) to create a more concentrated volume (Figure 8) of personal towelettes and excreta. It should be noted that other items (i.e., anal suppositories, etc.) were present and may have affected compositional consistency and biological degradation of the substrate. No attempt was made to remove these items.

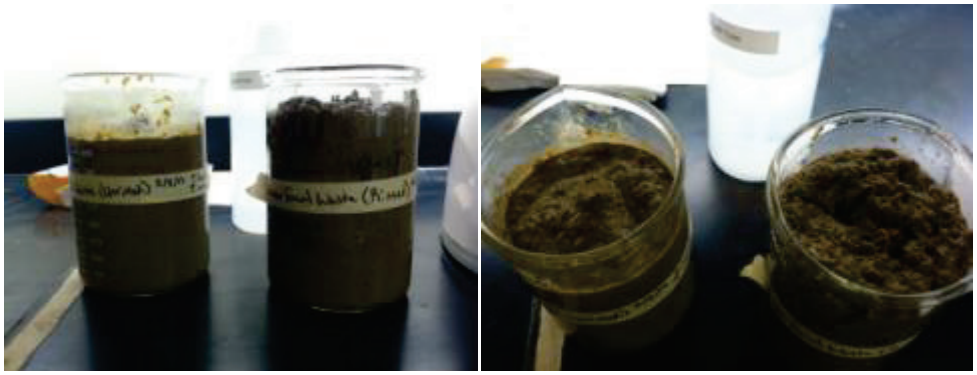
Figure 8. Original samples and samples after decant.

One of the two volumes was returned to storage at a temperature of ~5°C to be used later if needed. An attempt was made to separate the towelettes from the water and waste, but these attempts were unsuccessful due to the poor physical integrity of the wipes and the observed amount of waste that had adsorbed to the wipes. The contents of the decanted sample volume was scooped from the container and sieved at a nominal pore diameter of 2 mm (Figure 9). At this point, half of the sample was homogenized via blender (Figure 9), while the other half of the sample was rinsed using DI water while in the sieve before homogenization.

Figure 9. Sieve and blender.

The resulting substrate can be seen in Figure 10, as rinsed and unrinsed respectively.

Figure 10. Final condensed substrate and overhead of final substrate.



The resulting feed had an extremely low viscosity, which was overcome by diluting the substrate with DI water at a 1:1 ratio. The diluted substrate was then added to the batch reactors according to the schedule in Table 7.

Table 7. Characterization of batch reactors used in latrine waste study.

Reactor Number	Description	Substrate Volume (mL)	Seed Volume (mL)
1	Control	0	400
2	Control	0	400
3	Rinsed	200	200
4	Rinsed	200	200
5	Rinsed	200	200
6	Unrinsed	200	200
7	Unrinsed	200	200
8	Unrinsed	200	200

As discussed in the results section, there were problems with the results of the first latrine batch test. The second batch test for latrine waste was run for approximately 26 days, from March 2 through March 28, 2013, using excreta initially collected before the previous trial, and consisted of three jars of rinsed substrate, three jars of unrinsed substrate, and two control jars. The pH was measured initially but no buffer was added. Gas production of the seed culture was approximately 1.5 mL/day at the time it was removed from the mother reactor. These parameters are displayed in Table 8.

Table 8. Table for control and experimental variables for latrine waste study.

Reactor		Seed (mL)	Waste (g)	g-TVS	Water (mL)	Total (mL)	Initial pH	Final pH
1	Control-1	250	-	-	150	400	7.7	7.5
2	Control-2	250	-	-	150	400	7.6	7.5
3		250		3		400	9.1	7.9
4		250	177	3		400	9	7.8
5	Unrinsed	250		3	Add to fill to 400 mL	400	9.2	7.9
6		250		3		400	7.8	7.7
7		250	201	3		400	7.7	7.8
8	Rinsed	250		3		400	7.8	7.8

All eight batch reactor jars contained 250 mL of seed sludge from the Mother Ship. Unlike previous experiments with food waste and primary sludge, the latrine substrate took on a consistency similar to paste after homogenization. Therefore, the total volatile solids (TVS) to total solids

(TS) ratio of the paste was determined and the experimental reactors were each fed 3 g-TVS, which resulted in 177 g of unrinsed latrine waste and 201 g of rinsed latrine waste being applied to their respective jars. Tap water was added to all eight to bring the total active volume of each to 400 mL.

5-Liter Reactor Studies

Reactor

Tests were conducted in a 6-liter reactor from Ace Glass with an integrated water jacket for temperature control (Figure 11). Since the actual solution volume was approximately 5 liters, we refer to these studies as 5-liter studies. The reactor was sealed with a 5-port head. The center port was used for the mixer shaft, which was sealed with Ace Glass components and turned via an air-drive motor. One port was used to seal into the reactor a ⅜-inch outside diameter (OD) PTFE tubing through which food was introduced into the reactor. Two ports were used to seal into the reactor ¼-inch OD PTFE tubing. The first of these ports was used to sample headspace gas from the reactor, and the second was used to introduce nitrogen gas when flushing the reactor headspace. The final port was not used. The reactor also contained a bottom port through which mixed liquor was withdrawn from the reactor. The reactor temperature was maintained at 35°C by circulating water through the water jacket with a temperature-controlled recirculating water bath.

Foods

Food waste was obtained from the post concession located on Waterways Experiment Station in Vicksburg, Mississippi. Food consisted of scraps scraped from trays and some vegetables remaining in serving trays following the lunch meal. The entrée for the day was fried chicken, so a large fraction of the food scraps obtained included the skin and bones from fried chicken. The remaining meat on the bones was removed and bones were discarded. The meat scraps and vegetables were combined and placed in a food processor to break scraps down into small enough particles to be placed into a blender. The scraps were then blended into a homogeneous paste and stored in a refrigerator until needed.

Figure 11. 5-Liter reactor used in study.

Microbial Seed

The initial microbial seed to start the anaerobic digester was obtained from the primary anaerobic digester at the Vicksburg Wastewater Treatment Facility (Vicksburg, MS). The facility uses trickling filter technology as a secondary treatment, and primary and secondary anaerobic digesters to treat solids from the primary and secondary clarifiers.

Methods

Reactor Mixed Liquor Analyses

Samples were collected from the bottom port of the anaerobic digester into a 250-mL plastic cup while the mixed liquor was being vigorously mixed.

This sample was promptly divided into appropriate containers for analyses to be conducted.

Total Solids and Volatile Solids

Total and volatile solids were determined according to *Standard Methods* (Clesceri et al. 1998) 2540 B. and E., respectively, with one deviation. The samples were weighed, dried and burned in an aluminum weighing pans. Several empty pans were tested for loss due to ignition in the muffle furnace, and no significant loss of mass was measured. An alternative measurement to volatile solids that is commonly used is chemical oxygen demand (COD).[1]

pH

The pH was determined by one of two methods. The first method was used to obtain an approximate pH of the mixed liquor. A small portion of the mixed liquor sample was filtered through a 0.45-µm glass-fiber syringe filter and tested with a pH- sensitive strip, which indicated the pH in 1 pH unit between 1 and 12. Alternatively, the initial pH from the total alkalinity determination described below was used.

Total Alkalinity

The mixed liquor sample was centrifuged and the resulting supernatant was filtered through a 0.45-µm glass-fiber syringe filter. The clarified supernatant was tested for alkalinity following *Standard Methods* (Clesceri et al. 1998) 2320 B using a calibrated pH meter to an endpoint pH of 4.3 with a 0.02*N* sulfuric acid titrant. The initial pH of the test solution was recorded as the pH of the mixed liquor.

Volatile Acids

The mixed liquor sample was centrifuged and the resulting supernatant was filtered through a 0.45-µm glass-fiber syringe filter. The clarified supernatant was tested for alkalinity following Hach Esterification Method 8196 (Hach Company 2008).

[1] Teal, R. 2013. Personal Communication with Victor Medina, President, BIODICO.

Gas Analysis

Collection

Headspace gas from the anaerobic digester test vessel was collected by a sampling train consisting of a flow meter followed by several Tedlar gas collection bags connected to the reactor head via a combination of rigid PTFE (polytetrafluoroethylene) and flexible Tygon® tubing. Gas was collected in a sample train of six 5-L Tedlar bags pictured in Figure 12.

Figure 12. Gas collection for 5-liter reactor study.

The gas collection sample train was designed to collect the gas sequentially in bags with the use of one-way check valves and 25-mm syringe filters with 0.2-µm nominal pore value to act as pressure relief valves. This arrangement is illustrated in Figure 12. This arrangement did fill the bags preferentially from first to last in the sample train, but it did not produce temporally discreet samples. Actual pressure relief valves with the correct relief pressure would likely have produced the desired results.

Gas flow was measured by two Aalborg model GFM 17 gas mass flow meters (Figures 13, 14), each having a flow range of 0.0 to 10.0 sccm @ 70.0°F. The meters were attached to the sample train in parallel to double the flow range measurement capacity. The meters were factory calibrated for an operating fluid consisting of 60% CH_4 and 40% CO_2 at 16.69 psi absolute pressure and 70°F. The reading from each meter was recorded every 6 seconds via an external data logger and summed to estimate the total gas mass flow rates from the reactor.

Figure 13. Gas sampling train diagram for 5-Liter reactor study.

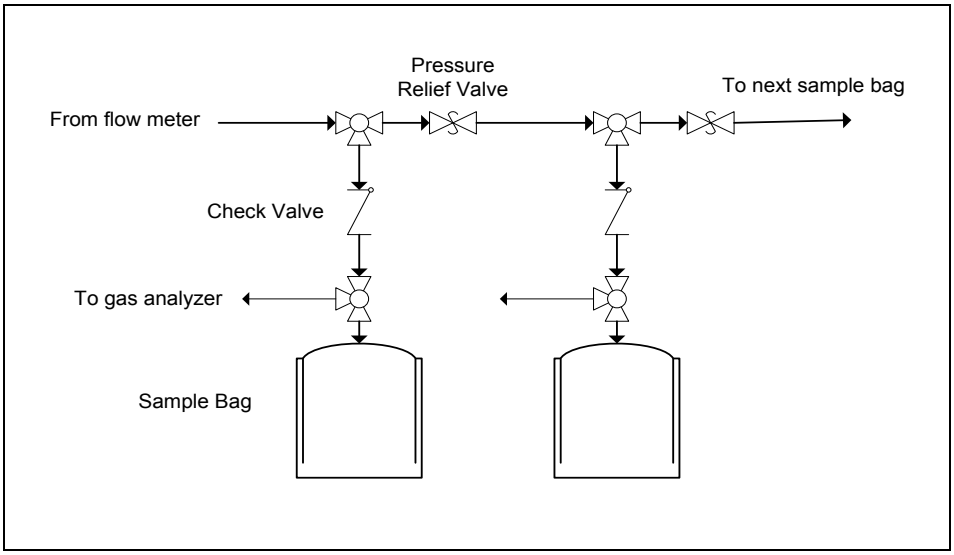


Figure 14. Gas flow meters for 5-liter reactor study.

Composition

The composition of headspace gas was analyzed for methane, carbon dioxide, and oxygen with a landfill gas monitor manufactured by Gas Data Ltd. (Coventry, United Kingdom) model LMSx (Figure 15). The instrument was calibrated by CEA Instruments, Inc. (Westwood, New Jersey) on November 20, 2012 for 0-100% CH_4 and CO_2 and 0-25% O_2 by volume. The instrument uses infrared detectors for methane and carbon dioxide determination and a fuel cell for determination of oxygen.

Headspace gas collected in each bag was drawn directly from each bag and analyzed separately. Headspace gas was also periodically drawn directly from the reactor for analysis, this step was typically completed immediately prior to feeding when mixed liquor was also drawn for analysis.

Figure 15. Gas analyzer for 5-liter and pilot reactor study.

Gas was analyzed individually from each gas collection bag by attaching the inlet tubing from the meter directly to the sampling port of each bag. Once the gas concentration for each bag was recorded, stable concentration readings were achieved after gas sampling from each bag began.

Methane Volume Calculation

Calculation of the methane quantity produced was achieved by using the flow rate and gas composition data. The methane concentration and volume of gas collected in each bag was used to calculate the average methane concentration of gas during a collection period, which typically lasted for approximately 24 hours. The average methane concentration was multiplied by the sum of the logged flow rates multiplied by the sampling interval to achieve a total volume of methane generated.

Field Reactor

A 45-gallon reactor was constructed at ERDC-EL (Figure 16a, b). It included a food processing unit that allows food to be directly fed into the reactor while being processed into an appropriate size for the reactor. The reactor was set up in a moveable trailer that contained the entire operation (Figure 17). Coiled tubing was attached to a pumping water bath that served as a heating system to allow operators to raise its temperature (Figure 18). A flow meter measured gas production (Figure 19), while a gas meter (Figure 15) measured methane concentration. Produced gas was

Figure 16a, b. Pilot reactor and food hopper/processor.

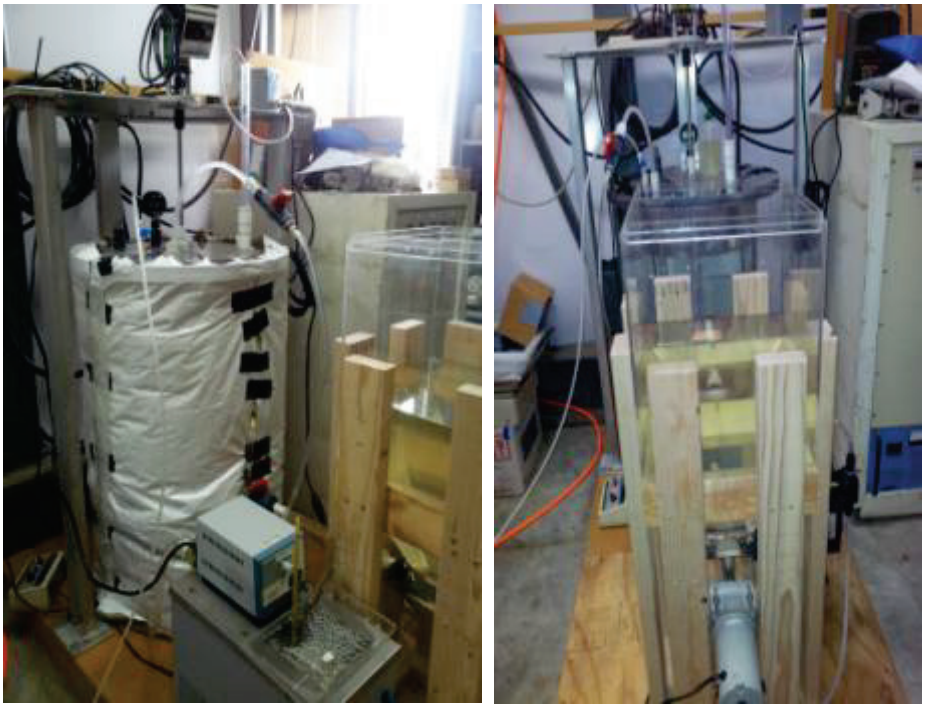


Figure 17. Set up of the anaerobic digester at LWI. Tedlar bags to collect gas on the upper right of the photograph, the one at the very end is expanded due to collected gas.

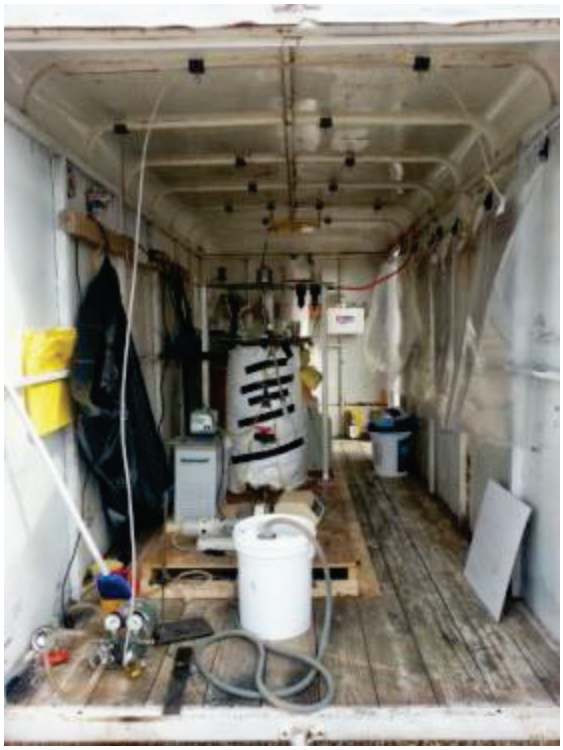


Figure 18. Bioreactor with insulation removed showing coiled tubing that was part of the temperature control system.

Figure 19. Gas flow meter used for the pilot reactor.

collected through tubing into a series of Tedlar bags (Figures 17 and 20). The reactor was fed food waste collected from an FLW DFAC, which, according to one of the authors (Robert Tucker), was similar to food that would be found at a FOB DFAC (Figure 21). Alkalinity, pH, and volatile acids were measured as discussed in the section above (Figure 22). The reactor was deployed at CBITEC from 15 August to 10 September 2013. The field study focused strictly on gas production.

Figure 20. Tedlar bags to collect generated biogas.

Figure 21. Food from a FLW DFAC used in the pilot reactor.

Figure 22. Field laboratory for alkalinity, pH, and volatile acids.

4 Results

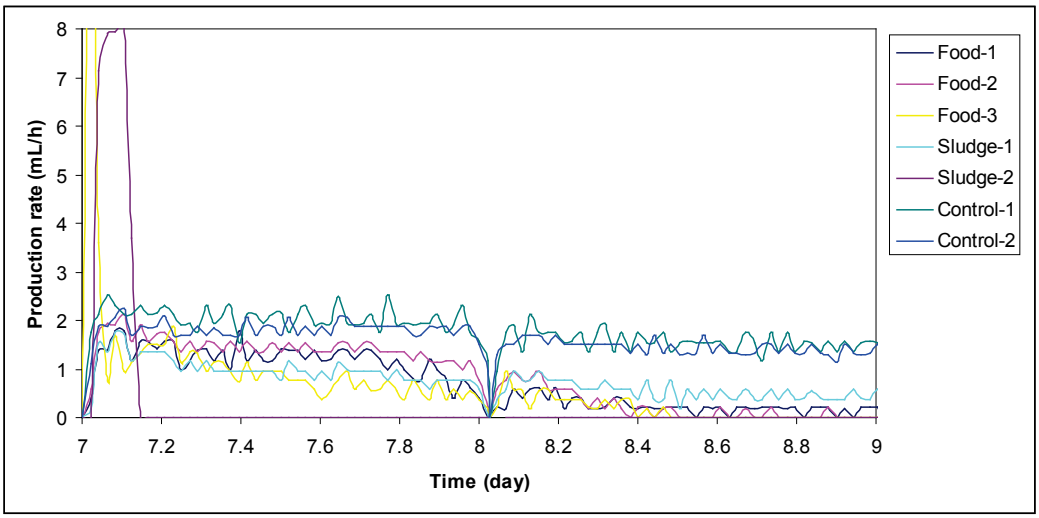
Microcosm Results

Food Study

Batch Tests 1 and 2

Batch tests one and two both failed due to rapid substrate degradation and pH decrease resulting from organic acid generation. In the first batch test, no alkalinity was added. After operating for 8 days, the pH in the reactors, dosed with food waste or sludge, decreased to approximately 5.3. As a result, biogas production stopped in the dosed reactors (see Figure 23).

Figure 23. Biogas production rate during first food batch test (from 7th day to 9th day) for food waste and primary sludge showing minimal gas production.



In the second batch test, alkalinity (K_2HPO_4) was added both initially and during the test to buffer the pH. After operating about 9 days, to maintain the pH in the reactor with food waste to about 6.8, a great amount of K_2PHO_4 was added (K_2PHO_4 concentration = 35 g/L). However, biogas production still stopped and pH had already decreased to inhibitory levels for methanogens (Figure 24 and 25).

The failure of these two tests suggests that food waste needed to be added slowly or in combination with other less labile wastes to balance the biological processes and avoid the rapid acid generation associated with the highly degradable and high biogas potential (energy-rich) food waste.

Figure 24. Cumulative biogas production during second batch test for food waste and primary sludge.

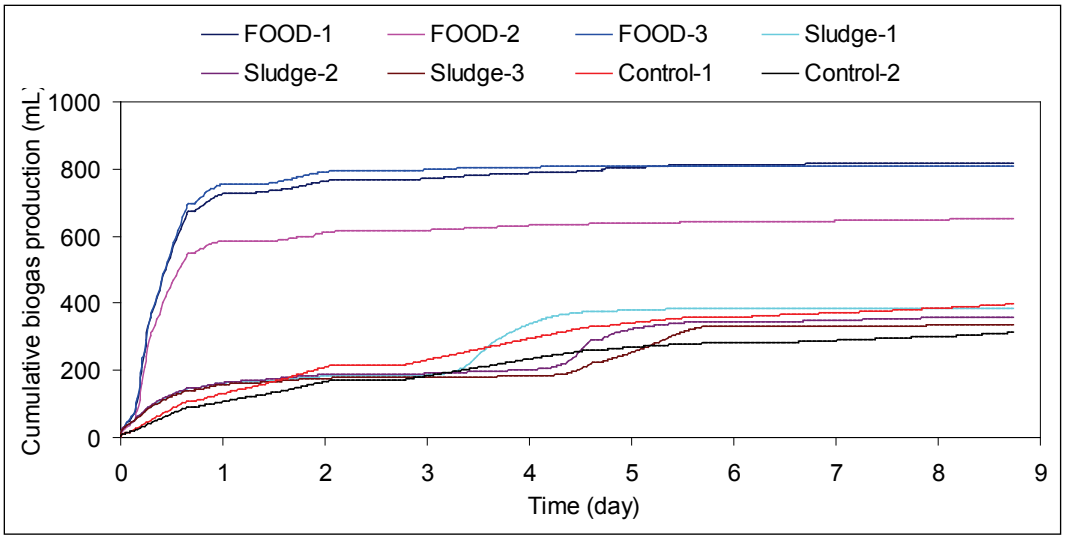
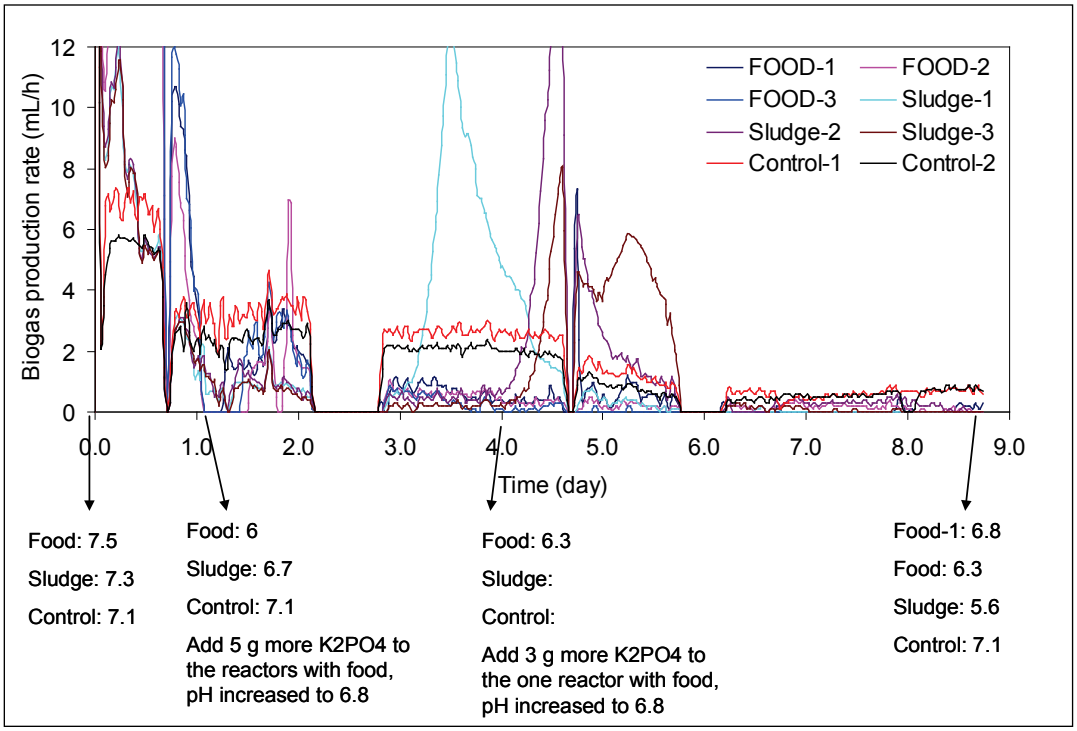


Figure 25. Biogas production rate during second batch test for food waste and primary sludge.

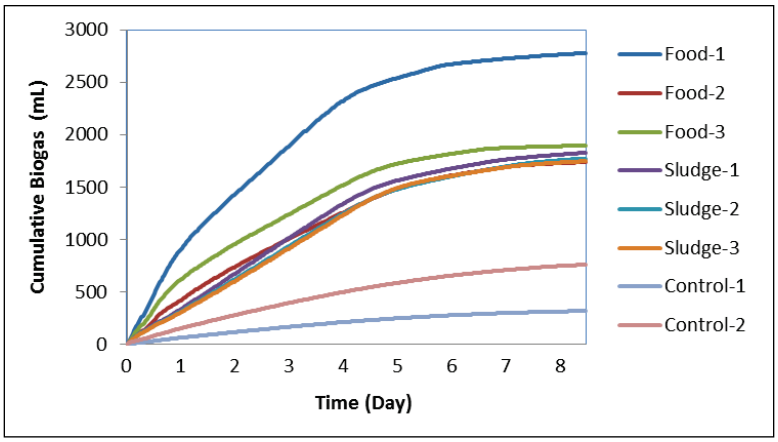


Third Batch Test

In third batch test only 3 g-TVSS food or primary sludge was used. Before adding the waste to the culture, the pH was increased to 9. Additionally, 2 g K2HPO4 was added to each reactor. Gas production of the seed culture was approximately 2.2 mL/day at the time it was removed from the

mother reactor. Figure 26 summarizes the results. Good gas production was found in the food and sludge reactors for about 5 days, then flattened. Both were substantially higher than control reactors, with food generally higher than sludge.

Figure 26. Cumulative biogas production during third batch test using food waste and primary sludge.



Low pH issue was solved in this test, resulting in more gas production. But the reproducibility for the control and food waste was not good. This necessitated the final, 4th test.

Fourth Batch Test

In fourth batch test, 3 g-TVS of food waste or primary sludge was added to each reactor (Table 4). Gas production of the seed culture was approximately 2.8 mL/day at the time it was removed from the mother reactor. Two control reactors without waste addition were prepared. The biogas yield rate for food waste and primary sludge were 0.87 ± 0.03 and 0.63 ± 0.01 L/g-TVS, both being significantly higher than the controls, and the reproducibility was acceptable: so the fourth batch test was successful (Figures 27 and 28, Table 9). These results indicate that food can produce about 30% more gas than typical sewage sludge digestion.

Latrine Waste Study

A batch test to measure biogas production potential for latrine waste with and without inhibitor was conducted. The latrine waste was rinsed with tap water, then decanted to dilute biological inhibitor. This was compared to material not rinsed. The latrine waste batch test was run for approximately 26 days through March 28. Table 10 shows the set up for each batch reactor before the test, and also includes final pH for reference.

Figure 27. Biogas production rate during fourth batch test using food waste and primary sludge.

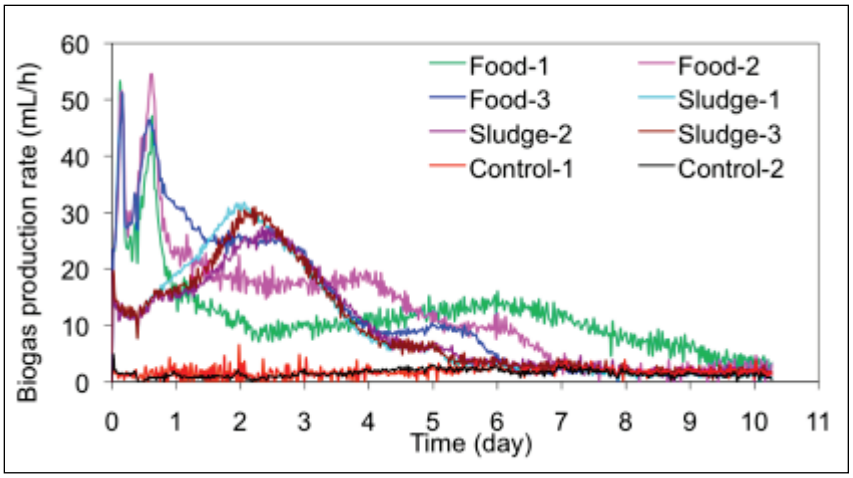


Figure 28. Cumulative biogas production during fourth batch test using food waste and primary sludge.

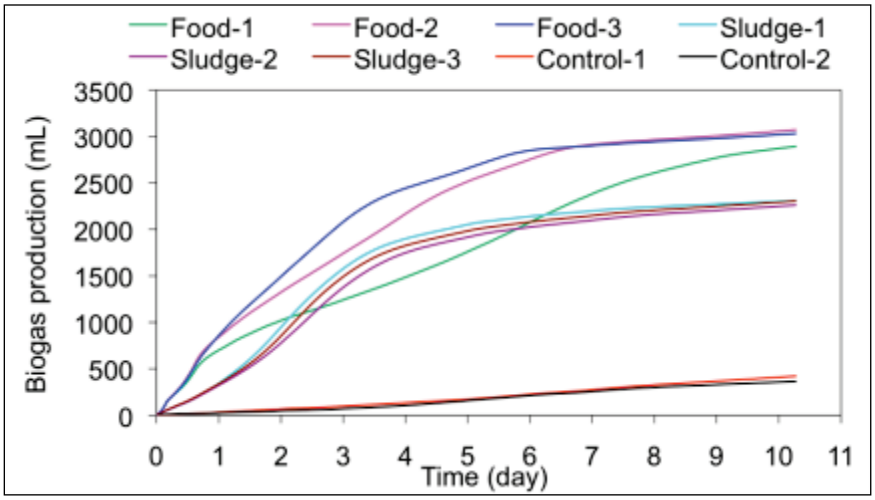


Table 9. Fourth batch test parameters for food waste and primary sludge.

	Food waste			Primary sludge			Control	
	F-1	F-2	F-3	S-1	S-2	S-3	C-1	C-2
Biogas (mL)	2892	3072	3032	2308	2261	2306	420	363
Mean (mL)	2501	2681	2641	1917	1870	1915	391 ± 41	
Specific Production Rates (L/g-TVS)	0.83	0.89	0.88	0.638946667	0.62318	0.63817		
Average Production Rates (L/g-TVS)	0.87 ± 0.03			0.63 ± 0.01				

Table 10. Table for control and experimental variables.

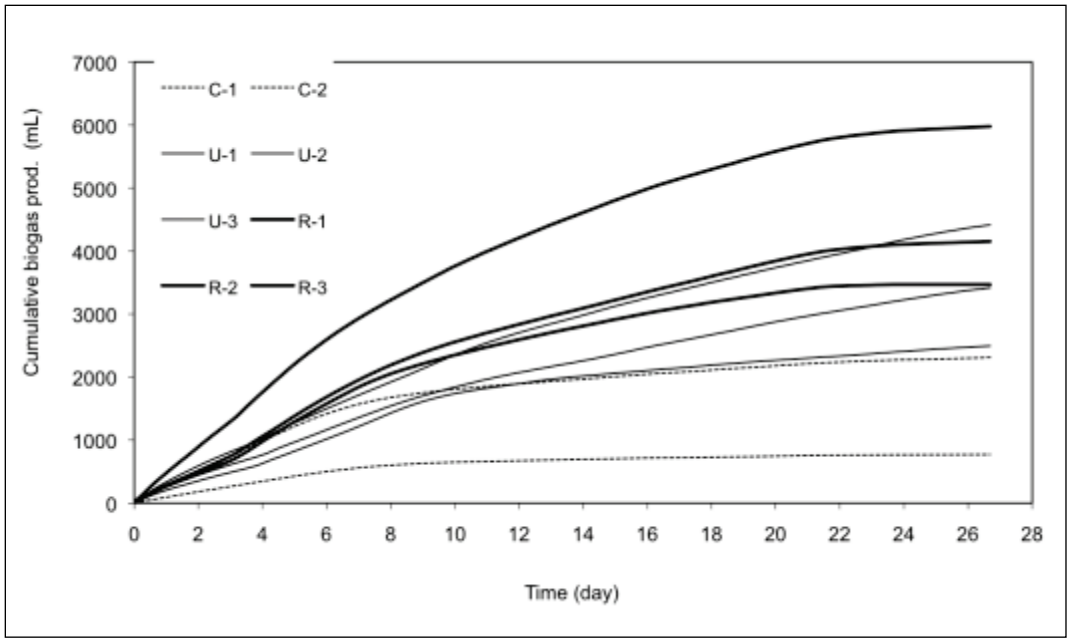
Reactor		seed (mL)	Waste (g)	g-TVS	Water (mL)	Total (mL)	Initial pH	Final pH
1	Control-1	250	-	-	150	400	7.7	7.5
2	Control-2	250	-	-	150	400	7.6	7.5
3		250		3		400	9.1	7.9
4		250	177	3		400	9	7.8
5	Not-rinsed	250		3	Add to fill to 400 mL	400	9.2	7.9
6		250		3		400	7.8	7.7
7		250	201	3		400	7.7	7.8
8	Rinsed	250		3		400	7.8	7.8

Unlike previous experiments with food waste and primary sludge, the latrine substrate physically had a consistency similar to paste after homogenization. Therefore, the total volatile solids (TVS) to total solids (TS) ratio of the paste was determined and the experimental reactors were each fed 3 g-TVS, which resulted in 177 g of unrinsed latrine waste being applied to three batch reactors and 201 g of rinsed latrine waste being applied to three batch reactors.

The initial pH of the not rinsed substrate was significantly higher than the initial pH of the control reactors and the rinsed substrate. The increased pH is the driving force behind the proposition that latrine waste not rinsed can potentially be used as a buffer for use during anaerobic digestion of food waste. The biological inhibitor is a caustic substance.

Figure 29 shows cumulative gas production over the duration of the batch experiment. The differences between control 1 (C-1) and control 2 (C-2) are stark, with C-1 producing more than double that of C-2. The not rinsed latrine waste (U-1, U-2, and U-3) seemed to have a greater lag in production than the rinsed latrine waste (R-1, R-2, and R-3). All of the rinsed latrine waste appears to be at or near a plateau in terms of net production by the end of the 26 days. However, the latrine waste not rinsed appears to continue to accumulate gas even at the end of the 26 days, which suggests the presence of inhibitor slows — but does not stop — biological degradation.

Figure 29. Cumulative gas production (mL) for latrine test.

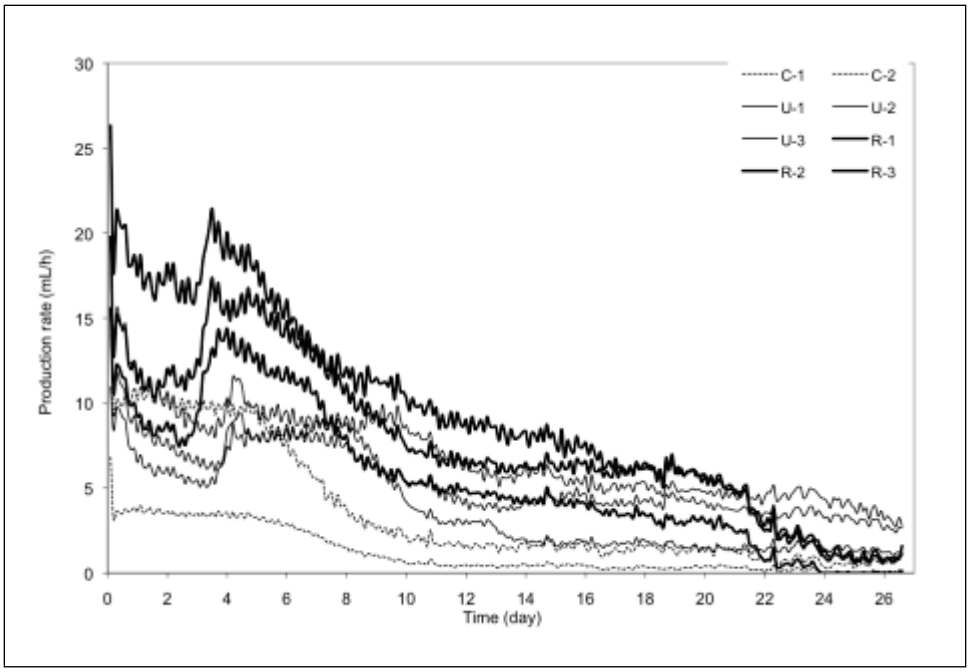


The biogas generation of the latrine waste was remarkably high, reaching levels of over 7000 mL, which were higher than the food waste. Perhaps the paste-like consistency of the wastes allowed for more efficient digestion, and more gas production.

Figure 30 shows the biogas production rate for the 26-day period. All of the experimental batch reactors underwent an apparent four-day lag period at the onset of the experiment. On or around Day 4, all six reactors had a marked increase in production rate, followed by a slow decline. The decline was more rapid for the rinsed latrine waste than the unrinsed latrine waste. In fact, at the end of the 26-day period, two of the unrinsed batch reactors had a higher production rate than all three reactors with rinsed substrate.

Both control reactors in Figure 29 underwent a relatively steady production rate, while substrate is used before declining on or around Day 4. Neither control reactor showed the characteristic spike in biogas production indicative of new substrate addition. The difference in rates between C-1 and C-2 remains a mystery.

Figure 30. Biogas production rate (mL/h).



One primary question entering this phase of biogas recovery investigation was whether the fiber in the wet wipes and tissue prevalent in latrine waste would biodegrade. At the end of the experiment, there was no noticeable fibrous material in any of the batch jars, suggesting that the towelettes had degraded.

The results revealed that that latrine waste that has not been rinsed is caustic and, therefore, may provide a buffer to the digestion of food waste. If this hypothesis is correct, then the blue-green water indicative of latrine waste may be a viable supplement for the caustic buffer added during food waste digestion. Rinsing resulted in increased biogas production kinetics. However, the total gas production potential was not significantly impacted. Latrine waste that has not been rinsed of biological inhibitor may ultimately generate the same volume of biogas as the rinsed substrate.

5-Liter Reactor Study

Treatment of Solid Feedstock Materials

The most critical aspect of an AD application to a CB is that it must satisfactorily treat the wastes, converting them into a form suitable for land application (even if they end up being landfilled). Figure 31 shows treatment of volatile solids in the reactor over an operation time of about

5 weeks. The team was able to steadily increase the influent volatile solids (VS In) while generally decreasing the MCRT, which was maintained on average between 40 and 60 days. Reduction of total volatile solids (TVS Reduction) increased during the operation. It was initially at about 55% reduction, then climbed to the high 70s%, then to over 80% reduction.

Figure 31. Influent volatile solids (VS In), MCRT, and reduction of total volatile solids (TVS Reduction) over time.

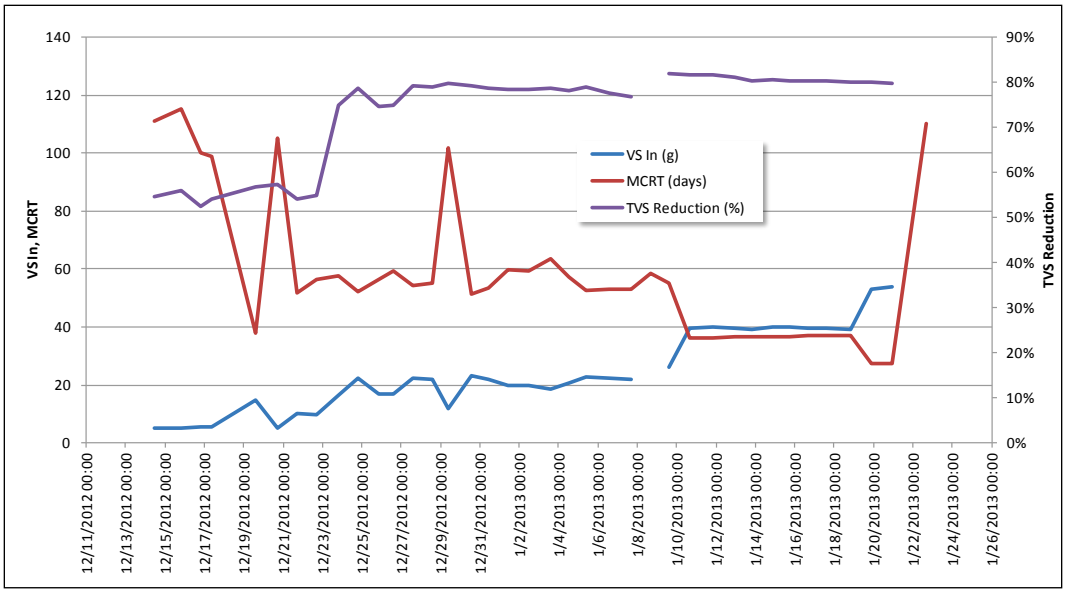


Table 11 summarizes the reactor performance over this 5-week period. Digestion of total solids resulted in a mass loss of 56%. Focusing on the volatile solids shows an average reduction of 81%.

Table 11. Treatment of solids in the 5-liter anaerobic digester reactor.

	Starting Concentration (g/L)	End Concentration (g/L)	Percent Removal (%)
Total Solids	280	123	56
Volatile Solids	240	47	81

Successful operation of an AD reactor is a balance between the food (total volatile acids [TVA as mg/L acetic acid]) and the total alkalinity (TALK as mg/L $CaCO_3$), which maintains the system's pH. According to Gray et al. (2008) the TVA:TALK ratio should be maintained close to 0.1. If this level gets too high, there is a risk of acid buildup, which will limit or even destroy methanogenesis and opens the door for the takeover of acetogens in the reactor. Control of the ratio can be obtained by controlling the reactor feed.

Because food has a high volatile acid content, particular care must be used with this material.

Figure 32 shows the concentrations of TVA and TALK in the reactors, as well as the TVA:TALK ratio. In general, the team was able to maintain reactor levels close to 0.1. Spikes did occur, each associated with feeding the reactor, but the reactor was able to self correct within a short period of time.

Figure 32. Total alkalinity (TALK) and total volatile solids (TVS).

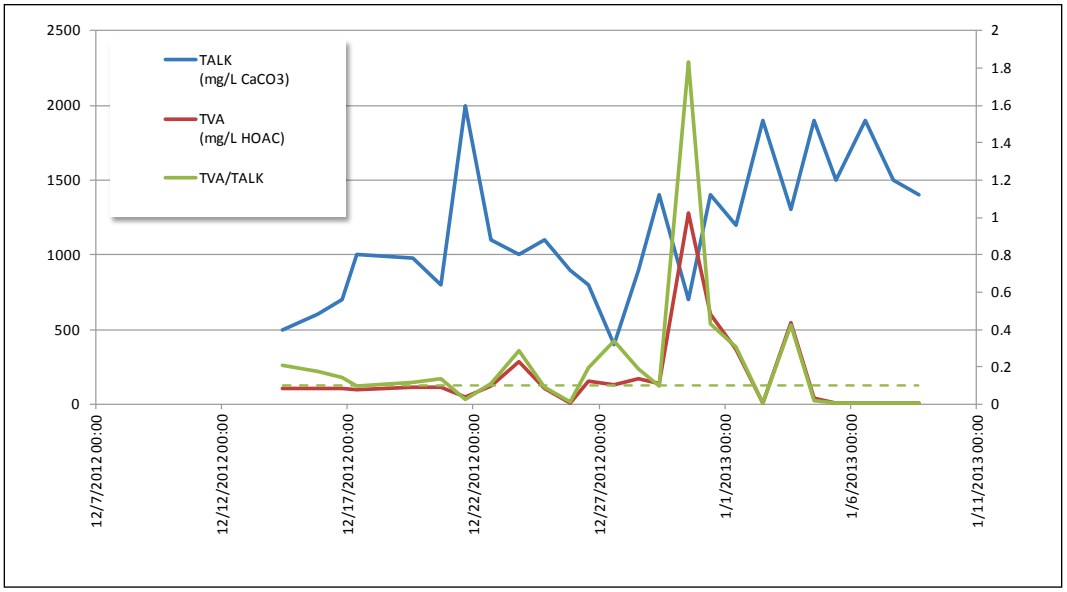


Figure 33 shows aluminum boats with dried and ashed samples from the reactor compared to the original food. Since the measurement used the same initial mass, you can see that the dried material in the anaerobic digester is larger in amount, indicating that the material loses water in its structure as part of the digestion process. Furthermore, the ashed sample for the AD treated sample is much smaller than that of the raw food. This shows the loss of volatile solids via biological degradation.

Gas Generation

Figure 34 shows gas flow measurements over a 4-day operational period. In general, the gas operated at a steady rate for a defined period of time, then dropped. Once the reactor received another dose of food, the flow rate would return back to the original level of 20 sccm. Average method concentration remained steady during reactor operation at about 60%, with spikes reaching 74%.

Figure 33. Dried and ashed food and AD samples.

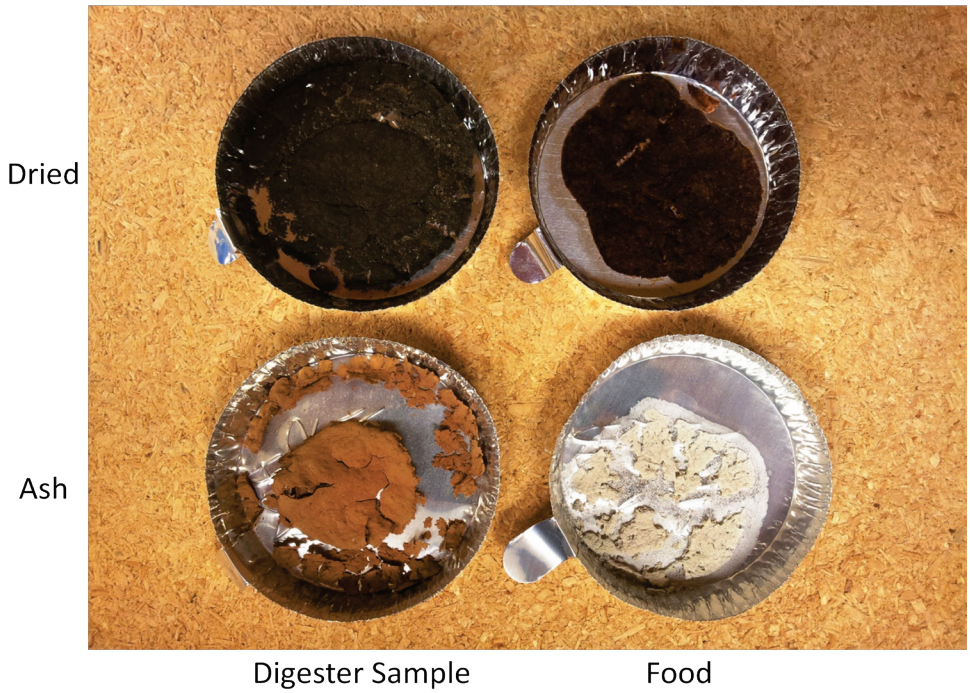


Figure 34. Gas flow and methane concentration over a 3-day period.

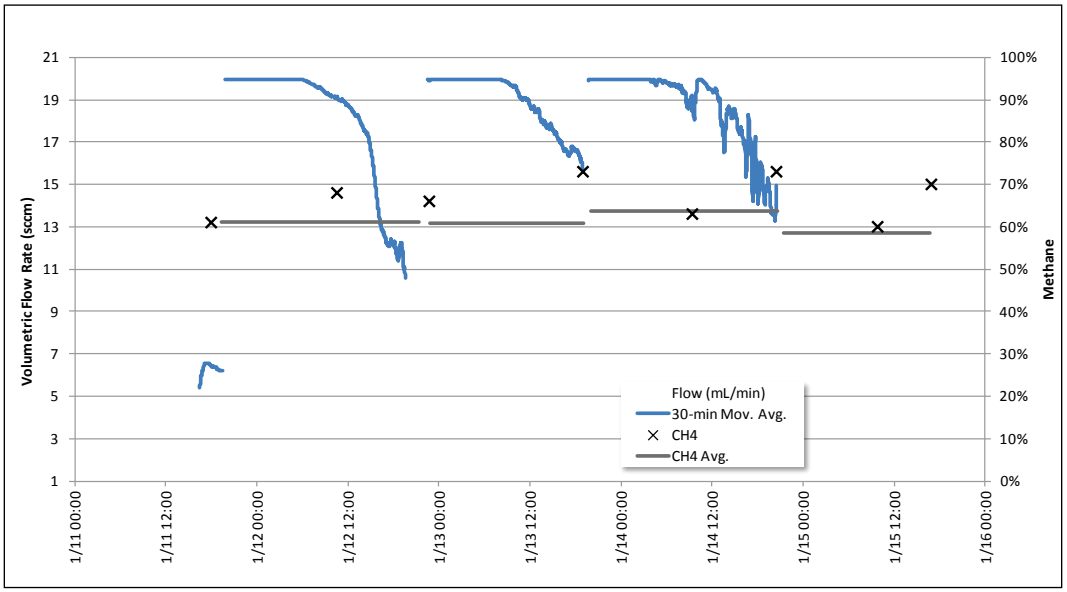


Table 12 summarizes gas production for the 5-liter reactor over a 5-week operational period. Gas production was more than 27 liters per day and the average methane concentration was 62%.

Table 13 summarizes methane production per unit waste and AD size.

Table 12. Average gas production data for 5-liter reactor study.

Total Gas Production (L/day)	27.2
% Methane	62
Methane Production Rate (L/day)	16.6

Table 13. Methane and energy production based 5-liter reactor studies.

CH_4 Production (ft^3/wet lb)	1.7
CH_4 (ft^3/dry lb)	6.1
CH_4 (ft^3/day/1000 ft^3 AD)	3000
Energy (BTU/dry lb)	6100
Energy (kWh/dry ton)	910

The gas was completely burnable (Figure 35). The generated gas potentially could be used for heating by burning it directly; it could be cleaned up and concentrated; or, it could be directly applied to a modern, military genset.

Figure 35. Burning gas from the 5-liter anaerobic digester.

Large Reactor Demonstration at CBITEC

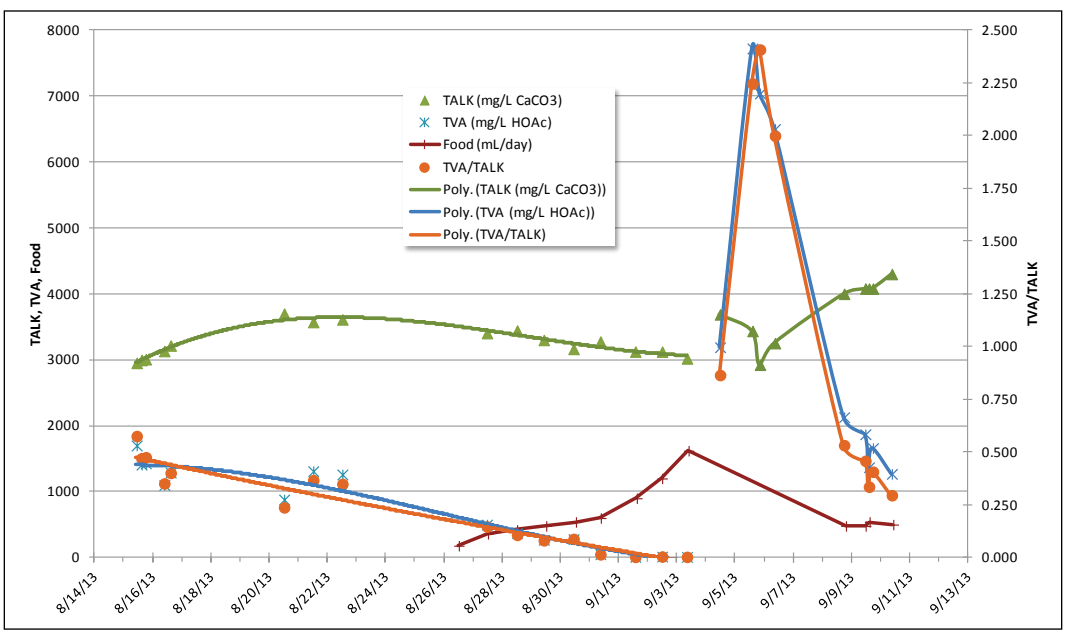
Reactor startup and operation

The reactor was deployed at CBITEC the week of 12 August 2013. Upon startup, there were several issues. Most prominently, the feed device quickly proved to be unsatisfactory for grinding and delivering food into the reactor. This required operators to manually grind food and push it into the reactor using 60 mL syringes. Also, the impeller mixing system did not work well, but a field correction was able to solve this problem. The reactor became operational on 15 August 2013, when it was seeded with sludge from the Northeast plant of the Urbana & Champaign Sanitary District (http://www.u-csd.com/index.htm).

Results

Figure 36 summarizes total alkalinity (TALK), the total volatile acids (TVA), and the ratio of TVA/TALK during the entire reactor operation from 8/15 to 9/11/2013. Food loading was not recorded until 8/26/2013, but the authors determined that reactor feeding was low and sporadic in the timeframe between 8/15 and 8/26/2013.

Figure 36. Food, alkalinity, and volatile acids data from field demonstration.



The TVA/TALK ratio is an important operating parameter for anaerobic digestion. If the ratio is too low, this indicates that the reactor is being starved, and gas production would likely be low. However, too high of a

ratio can indicate a buildup of acids, which can result in a decline in methanogenic activity and, in extreme cases, a reactor crash. As mentioned earlier, Gray et al. (2008) indicated that a goal for a healthy reactor is a TVA/TALK ratio of 0.1. However, because their reactor focused on treatment of sewage sludge and this reactor is primarily focused on food, it is likely that a higher TVA/TALK ratio would be appropriate, perhaps on the level of 0.3 to 0.5.

The TVA/TALK ratio steadily declined from reactor startup on 8/15 to 8/26/13, indicating that inconsistent feeding was resulting in reactor starvation. The team began to take more detailed food input data beginning on 8/26/13, and began to steadily increase reactor feeding. The increase in feeding appeared to increase microbial activity, but the team eventually found a rapid increase in the TVA/TALK ratio, so the feeding rate was eventually reduced again.

Figure 37 summarizes gas production data from the reactor from 8/26 to 9/10/2013. Unfortunately, the team had some problem with the flow totalizer prior to 8/26/2013. Observation of the Tedlar bags indicated that there was an immediate production of gas when the reactor was seeded. However, from 8/26 to 8/26/2013, observations of the Tedlar bag traps indicated virtually no gas was produced. This flat production appeared to be due to relatively low feeding rates described in the paragraph above. Beginning on the 26th, the authors began a regimen of systematically increasing the reactor feeding. Gas production steadily increased with this new regimen. On 9/5/2013, the gas totalizer was reset during some maintenance to the system, but subsequent measurements showed an exponential increase in gas production, even as reactor feeding was decreased to address high TVA/TALK ratios (Figure 36). Gas production eventually reached levels as high as 300 L/day and total gas increased to over 1100L in the 15-day period from 8/26 to 9/10/13.

The methane content of the gas generated was measured by running gas collected in the Tedlar bags through the gas analyzer (Figure 38). These measurements ranged from 65 to 70%. This gas could be burned without any treatment, and was used to percolate coffee as part of the demonstration (Figure 39).

Figure 37. Gas production data from field demonstration.

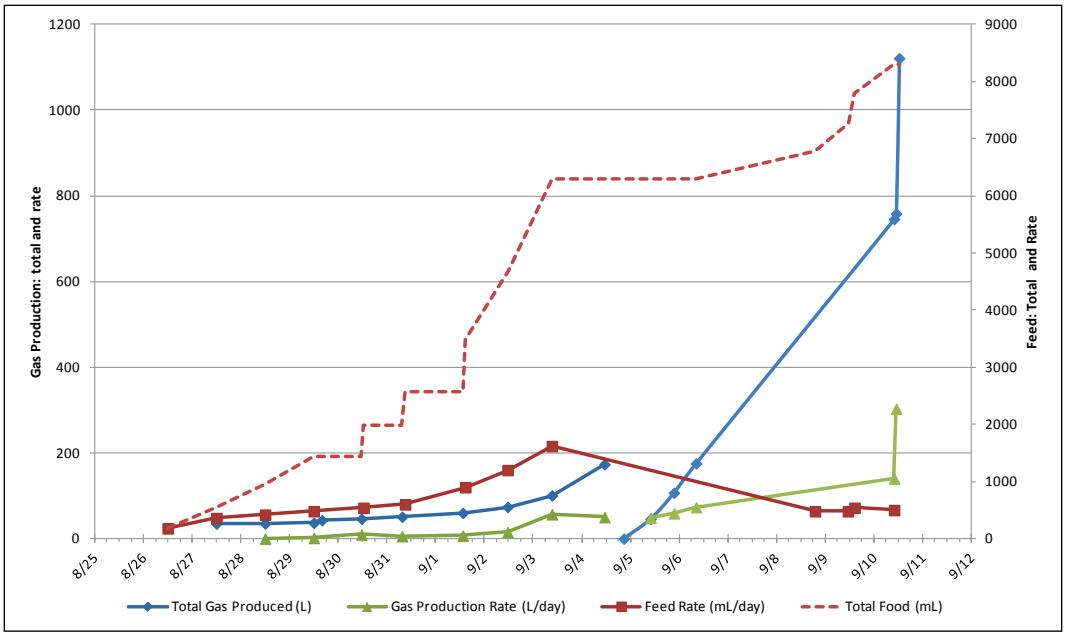


Figure 38. Gas meter reading on biogas stored in Tedlar storage bag showing methane content at 68%.

Figure 39. Demonstration using the generated biogas to percolate coffee.

5 Discussion

Treatment of Food and Blackwater Wastes

The authors' studies show that the anaerobic digestion was an effective means of treating food waste and blackwater. In the case of food waste, solids reduction of over 50% was achieved, with over 80% reduction of the volatile solids. The 80% reduction of TVS is supported when compared to similar studies exploring food degradation in ADs (Arcadis/Malcom Pirnie 2012, Gray et al. 2008, Vlachopoulou 2010). This level of reduction is considered excellent performance, and it is well above the average volatile solids reduction found for municipal solids treatment, which typically ranges from 50 to 60% (Gray et al. 2008). In addition, EPA 503 regulations require a 38% reduction for land application (USEPA 1994); the reactor performance far exceeded this requirement. Therefore, these reductions are consistent with stabilizing these materials, allowing for safe use of the digestate directly as soil amendment.

The digestate solids could be managed by land application or by disposal (landfilling). Land application would be the most beneficial reuse, and digestate solids are typically regarded as beneficial and can be used as a biofertilizer for land applications (Lim et al. 2012). The value of land application on the CB is probably limited, although there might be some use for green areas like sports fields, gardens, or parade grounds. Consequently, land application would probably require interaction with the local population. Such interaction is considered potentially beneficial as part of a Full Spectrum environment. The digestate could be distributed to the local population as a soil amendment for agricultural purposes, as these treated biosolids have the ability to stimulate crop growth.

As discussed in the introduction, food waste is a substantial part of the wastestream at a typical CB, and is very difficult to manage because of disposal, putrescence, and pest issues. Blackwater is also an unpleasant wastestream that is challenging to manage. This study indicates that AD can be an effective treatment for these critical wastestreams.

Energy Production

The results in this study indicate that when operating properly, the food-waste-rich waste stream expected at CBs would generate relatively large volumes of relatively high methane gas. The food microcosm study (Table 4) showed that food generated statistically higher gas volume than equivalent amounts sewage sludge. This is supported by a review of the literature, which shows that food generates more gas of better quality compared to other feedstocks commonly used for ADs. For example, Gray et al. (2008) found that food waste generated close to 25% more energy per wet ton compared to that of municipal wastewater solids, and Vlachopoulou (2010) found that food was more effective per unit mass than sewage sludge at gas production. Furthermore, both of these studies had methane concentrations approaching 70% for food treatment. A study conducted by Arcadis/ Malcomb Pirnie (2012), on the other hand, had less impressive gas production, and the methane concentration was only 54%.

Limiting food waste in the first place, of course, makes a lot of sense (Baker and Vandepeer 2004), but it is in fact challenging in a CB environment. Soldiers must be well fed to operate at peak conditions in stressful environments. Additionally, soldier morale is enhanced by having a variety of food options. More food options present more opportunities for food waste.

As shown in Figures 35 and 39, the 60 to 70% methane-containing biogas can be directly burned, and can therefore be directly used for heating, cooking, and lighting purposes (Lim et al. 2012). In the past, most electrical generation equipment required high purity methane gas (>90%) to operate properly. However, advances in co-generation system makes biogas also directly usable in modern generators without the need for cleanup (Viquez et al. 2008, EWG 2012).

A novel approach that could be developed in the future would be to use anaerobic digesters to provide fuel for hydrogen fuel cells. Such a system has been developed and used at the Sierra Nevada Brewery in Northern California (Gekas 2009, Sierra Nevada Brewing Co. 2012). In this case, methane is converted to hydrogen gas, using a series of catalysts, and the gas is then used in a fuel cell. Fuel cells provide long-term storage of chemical energy and would serve to concentrate the energy in the biogas; this process might be an ideal means of energy supply at a CB. A key challenge would be addressing impurities, like hydrogen sulfide, which can

poison most fuel cells, but pretreatment approaches could be developed to address that problem.

Using the assumption of 2 lbs of food waste per soldier per day (roughly based on USAES 2010), the team estimated the energy that could be generated from AD of these materials. Table 14 summarizes the estimated energy production from three CB sizes (250, 1500, and 5000 person), with the estimated energy needs for camps of these sizes (EWG 2012, see Table 1). Appendix 1 contains the computational table and the assumptions used. Based on this analysis, it was determined that each person would generate about 0.25 kW per day and that AD could provide 18 to 30% of the energy needs of CBs. Of course, some of the energy would have to go back into the waste management system, including processing the food and other wastes (grinding, pulping. etc) and potentially heating the reactor to reach mesophillic conditions (35C). At the same time, existing waste management has energy costs, particularly transportation and landfilling, which may ultimately be much higher. A key assumption in this analysis is that a field unit could maintain levels similar to the laboratory (5-liter reactor) study.

Table 14. Estimated daily energy generation from AD of food wastes in an FOB environment and comparison to estimated daily energy requirements (from EWG 2012).

Camp Size	Estimated Total Energy Required by FOB (kWh*)	Calculated Energy Production from AD of Food Wastes (kWh)	Percent of Total Potentially Provided by AD
250	270	62	23.0%
1500	2000	369	18.4%
5000	4000	1231	30.8%

* EWG gives power requirements in kW and MW. Energy is given as average power over the course of one hour, in this case kWh.

We can relate this energy to fuel usage and costs based on the standard fuel used by the US Army is JP-8 (Table 15). These indicate that the energy generated by an anaerobic digester can save 500 to over 11,000 gallons of fuel a month depending on the camp size. The cost savings from fuel ranges from just over $2000 to close to $130,000 per month, and if we consider the complete list of factors — particularly force protection costs associated with air support for fuel delivery costs — the savings can be as high as $500,000 per month, for just one camp. This analysis, of course, makes the assumption that the biogas can directly displace the use of JP-8. In some cases, that might not be feasible, particularly where the high energy density of liquid fuels are needed. For example, use for vehicle operation is not currently practical. Nonetheless, the potential for savings is interesting.

Table 15. Estimated displaced fuel volumes and costs from estimated energy production from anaerobic digestion at three sizes of forward operating bases.

Camp Size	Calculated Energy Production from AD of Food Wastes (kWh)	Estimated JP-8 Fuel Use per Hour (gal)[1]	Estimated JP-8 Fuel Use per Month (gal)[2]	High and Low Estimated Monthly Cost	Fully Burdened Fuel Costs
250	62	0.77	554	$2,216 to $6,371	$24,930
1500	369	4.6	3312	$13,248 to $38,088	$149,040
5000	1231	15.5	11,160	$44,640 to $128,340	$502,200

[1]Assumes an energy density for JP-8 of 42.8 MJ/lb (Bisio 1995), a liquid density of 6.7 lb/gal (based ion Bowden et al. 1988), and a conversion of 3.6 mJ per kWh.

[2]Assumes a 30-day month.

[3]Fuel cost from estimated by the two scenarios from the Army Environmental Policy Institute giving a range of $4.00 to $11.50/gallon (Eady et al. 2006). Costs are consistent with those estimated for in theater by Noblis (2010).

[4]Fully burdened costs includes costs for force protection, particularly air support for convoys, giving a cost of $45.00/gallon (Noblis 2010).

Gas production from the latrine wastes were not studied in the same detail as the food wastes, but were also very promising. In fact, cumulative production was actually higher in the latrine waste than in the food waste. Furthermore, toilet chemicals did not appear to be completely inhibitory, with the final gas volume produced being about the same as latrine wastes, with the inhibitory chemicals removed by rinsing.

Energy production from AD can be substantial. For example, recently, a business section of Fort Collins, CO, became the first net zero energy district on record in the United States, which means that it generates as much energy as it consumes (Berton 2013). This accomplishment included the development of highly energy efficient businesses and the use of solar power. However, the primary energy production offset was achieved by a large anaerobic digester that was used to treat brewery wastes at the new Belgium Brewing Company (http://www.newbelgium.com n.d.). A combination of improved energy efficiency along with novel waste to energy approaches, which would include AD, could make the concept of a net zero energy CB a reality in the next 5 to 10 years.

Key Issues

Seeding

One issue raised in this study is reactor seeding. Reactors need an established culture of methanogenic microorganisms. Obtaining these seed cultures in the United States is relatively easy, as anaerobic digestion treatment is fairly common for municipal wastewater treatment sludge and for industrial wastewater sludge. However, for projects in areas requiring CBs, these sources might not be readily available. Microbial seed packages are common for wastewater treatment and for soil and groundwater remediation, but the team was not able to identify any for anaerobic digestion.

One potentially widespread source is manure from ruminant organisms, such as cattle, sheep, and water buffalo. These organisms are very common as domesticated animals are found throughout the world (Hackmann and Spain 2010), so obtaining manure from these organisms would likely be easy in most settings. Reports indicate that ruminant manure is a very effective seed, and AD is routinely used effectively for animal waste treatment. Actually, any concentrated organic material in an anaerobic setting could work. For example, a microcosm mother reactor was actually seeded with hog manure waste, which is not a ruminant organism, but it worked well nonetheless.

Inhibitory Issues

Inhibitory substances can affect all forms of biological activity. However, anaerobic processes tend to be even more sensitive to inhibitory substances (Rittmann and McCarty 2001). One reason is that to create anaerobic conditions, organic matter must typically be concentrated, which concentrates any associated inhibitory substances. In addition, since anaerobic respiration is less efficient, organisms must consume more organic material to obtain the same energy, resulting in more exposure.

Acetogenisis

Anaerobic digestion is a well-established process that is used throughout the United States (Goldstein 2000) as well as in many other parts of the world, both in developed (Browne and Murphy 2013) and developing nations, (Viquez et al. 2008) to treat sludges and highly organic wastes. However, it is also a sensitive process that can periodically fail. The

challenging aspect in AD is the balance of keeping an active methanogenic population while limiting the growth of acetogens (Gray et al. 2008). This requires a strong balance of system alkalinity and volatile solids. If this balance is not maintained, the reactor can be overcome by acetogens and fail.

In both the microcosm study and in the 5-liter reactor study, initial efforts to set up studies were affected by pH declines commonly found with acetogenesis. Although these were corrected in subsequent studies (for the microcosm study, a buffer was used and feed rate was reduced and for the 5-liter study, the TVA:TALK ratio was periodically monitored and feeding was adjusted based on this data), this issue would be of concern for a field operation. To make things more complicated, TVA and TALK are wet chemistry methods that would probably be cumbersome to conduct in the field by untrained personnel.

Certainly the use of pH buffers could be useful, but this would create a new material that would have to be delivered to the FOB. The best approach would be to develop easy-to-use guidelines in feeding the reactor. Since the exact numbers would vary depending on the reactor and its capacity, the Army could specify that any commercial reactors must provide this guidance on their individual systems.

Staffing for such a reactor is an issue that must be solved by the Army. Ideally, it would be best if operation of such reactors could be incorporated into existing jobs. One possibility is that the cooks themselves could manage this process as part of their duties. But it is possible that more complex waste management may require a new soldier qualification, known as a Military Occupational Specialty (MOS), which could be established by the Maneuver Support Center of Excellence (MSCoE).

Fats, Oil, and Grease (FOG)

FOG is generally a beneficial component in anaerobic digestion, as it typically results in increased gas production and quality (Cockrell 2008, Gray et al. 2008, Kabouris et al. 2008). However, at very high levels, FOG can build up in the reactor, and this can ultimately result in a retardation of methanogenesis (Gray et al. 2008). The authors believe this hampered the performance of the 5-liter reactor after an extended period of effective operation.

This problem could be effectively addressed in several ways. Limiting FOG loading could be one possibility; however, since most soldiers tend to crave food high in FOG, limiting its loading might severely affect the applicability of AD reactors. Since FOG tends to self separate and float, skimming could be an effective means of controlling high levels. Another approach could be to add materials that could sorb excess FOG. Pulverized paper is commonly found at FOBs, and could be a useful additive for this purpose.

Pretreatment

Anaerobic digesters tend to work more efficiently and produce more biogas when mechanical, thermal, chemical, or biological pretreatment of feedstock is performed (Appels et al. 2008). This type of pretreatment can result in the disintegration of sludge cells, which will transform the organic material into more biodegradable materials (Appels et al. 2008). Exploring appropriate pretreatment could be valuable.

Other inhibitory issues

Military food is typically heavily salted, and this could potentially lead to salt buildup that stifles biological activity. This was believed to be an issue with one of the early unsuccessful operations of the microcosm reactor study. Another issue commonly found with food waste AD is the formation and accumulation of ammonia, which also can retard methanogensis (Vlachopoulou 2010).

Operational Issues

This project consisted of three experimental efforts, the microcosm experiments, the 5-liter reactor study, and the field demonstration. Each study revealed issues associated with operations. In the microcosm study, over-feeding resulted in acidification, which required buffering and adjustments to the feeding schedule. Similar issues were found in the 5-liter reactor study. And in the large reactor study, underfeeding resulted in a prolonged period of little or no gas production. Although each of these were overcome, they do indicate that anaerobic digester reactors can require significant expertise and attention to properly operate. In an FOB deployment, this kind of attention and expertise might not be readily available. Addressing these issues may ultimately determine whether such reactors are practical for FOB applications. Three approaches could

eventually be important. The first is automation, which may allow for a reactor to literally adjust itself, reducing operator requirements. A second approach is the development of specific operational requirements that could keep the reactor working provided they are followed. Finally, remote operation could be valuable, allowing for skilled operators to direct the reactor operations without needing to be at the FOB itself.

Combined Waste Treatment

A common theme in the previous discussion sections is that although food wastes generate relatively large volumes of good quality biogas, the process has inherent instabilities that can result in failure. Although failures are not catastrophic, the solution typically involves reseeding and restarting the reactor, which can be time-consuming. Developing more stable processes would be desirable. The solution may be relatively simple but still beneficial: including other lower energy waste streams into the AD. Vlachopoulou (2010), for example, found stable AD reactor performance when food wastes were mixed with municipal biosolids.

There are numerous options in a CB environment. One obvious solution is wastewater and wastewater treatment sludge (if the CB has a wastewater treatment system). In fact, the team included treatment of blackwater as part of this study. One issue concerns whether toilet chemicals are used, but the team's limited study of that issue in this project indicated that these do not halt methanogenic reactions. Greywater could also be included. As discussed above, the authors speculate that pulverized paper might be a great material to include in the process, because it could absorb inhibitory substances. Solid waste surveys in Kosovo found significant amount of grass cutting waste (Gerdes et al. 2006) that would also be treated by AD.

Another substantial waste stream at CBs is post-consumer food and paper/plastic food service items. Incorporating these materials into an AD system would be challenging because it would be necessary to either separate out the plastic materials or use biodegradable plastics or substitutes. However, a pilot study conducted by Arcadis/Malcomb Pirnie (2012) at Eglin Air Force Base found that paper towels and paper napkins could be effectively included in an AD system. El-Mashad et al. (2012) found that biodegradable plastics and other biobased products were effectively degraded in anaerobic systems. Anaergia, a company focused on anaerobic systems, indicates that — in fact — plastics can be incorporated into an AD

system, provided they are reduced in size by hammermill operation (http://www.icontact-archive.com/9-_swTffyq83xPKYnrflkxIB6-OQP1Sm?w=4&goback=%2Egmp_72734%2Egde_72734_member_237676842). Not only would including other wastestreams serve to stabilize the AD process, but they would expand the utility of the treatment to a larger portion of wastes at an FOB.

Utility for Contaminated Soils

Anaerobic processes have been proven to be effective for a variety of contaminants, which could be found at FOBs, including explosives (Medina et al. 2012), perchlorate (Medina et al. 2006, Morrow et al. 2010) and chlorinated solvents (McCarty and Semprini 1994). Generally, the degradation of petroleum hydrocarbons is conducted aerobically; however, these can also be degraded anaerobically (Boopathy 2003, Boopathy 2004, Coats et al. 1997, Grishchenkov et al. 2000, Hunkeler et al. 1998). Scherr et al. (2012) describes treatment of petroleum-contaminated soils in actual anaerobic digesters. They found small, but significant, degradation of the petroleum hydrocarbons and determined that the microbial consortium does appear to adapt to degrade the petroleum constituents while maintaining methane production. An aerobic digester might, therefore, prove to be a useful means of treating small soil quantities. Focused testing could be useful in this regard.

Biogas Storage, Use, and Safety

Biogas generated by an AD system on a FOB could be easily collected and stored in balloon-like plastic or latex bags, which are common in Asia and South America for collecting biogas (Figure 20, Viquez et al. 2008). These can be easily moved from place to place as needed. Alternatively, the gas could be pressurized into cylinders. This would make the gas more compact, but would require an additional energy use to compress the gas.

In a combat environment, biogas could be impacted by enemy fire. The gas could then be a flammability hazard. However, liquid fuel that is currently being used could be impacted by enemy fire as well. The moderate methane content of the biogas would make it far less of a hazard than liquid fuels. If the gas was not pressurized, its hazard would be further reduced, although it would take up significantly more space.

Figure 40. Non-compressed biogas stored in large plastic bag (Lansing and Moss 2010).

Transition as Part of Full Spectrum Operations

Jones (2011) describes a biogas plant constructed near Kabul, Afghanistan, as part of an International Security Assistance Force (ISAF) program to improve environmental conditions, provide construction and operational jobs, and produce biogas for energy. The biogas plant would operate primarily on animal wastes, which are common in the area. In addition to operation, the biogas plant was intended to provide training for other installations planned in Afghanistan. In a similar manner, anaerobic digestion was planned for managing human wastes throughout Afghanistan, led by MAJ Edward Mears (Maryniak 2011). It is logical to assume that such plants could be viable transitional technologies in many other places where the Army must operate in the future.

Recommendations for Future Studies

Some additional studies could be valuable, including:

- studies using native materials for reactor seeding, including ruminant animal waste;
- large-scale demonstrations using a commercially available anaerobic digester design tailored to CB solid (biodegradable) wastes;
- studies focusing on cost-effective energy recovery;
- simple operation and monitoring technology with unskilled operators; and
- studies with simple engineered systems that can be inexpensively constructed on site for smaller CBs.

6 Conclusions

The following conclusions were derived from this study:

- Anaerobic digestion (AD) is a promising approach for managing wet wastes (food and black water) found at FOBs:
  - Treatment resulted in over 50% reduction of the total solids and over 80% reduction of volatile solids. This indicates that the resultant material is well treated and would no longer be subject to putrifaction.
  - Volumetric gas production was vigorous, and the average methane concentration was over 60%, which is easily burnable.
- Some problems would have to be addressed to make the approach applicable to FOB environments:
  - Solutions to seeding the reactors in remote environments are needed. One possibility is the use of excrement from ruminant organisms, which are commonly domesticated throughout the world.
  - The wastes, particularly food, must be processed into small pieces before application to the reactor. This effort would probably not be feasible in a CB setting; however, it is possible that automated feed and processing systems could be developed.
  - Monitoring reactor performance requires the measurement of alkalinity and volatile solids. These are both wet chemistry approaches, which would probably be difficult to perform in most CB settings. There does not appear to be an easy alternative to these measurements. Instead, it may be necessary to have strict operating restrictions in place to keep the reactor functioning properly.
  - Acetogenesis occurred in both reactor studies, suggesting that this could be a key issue with the food-rich streams expected at CBs.
  - The 5-liter reactor appeared to have issues associated with the buildup of FOG, which is expected with the food rich stream. The authors believe that paper might be a useful material to address this buildup, as it may absorb a significant amount of this FOG.

References

Appels, L., J. Baeyens, J. Degrève, and R. Dewil. 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Progress in Energy & Combustion Science* 34(6): 755-781.

Arcadis/Malcolm Pirnie. 2012. Task 2. *Extended pilot test report and pre-processing plan*. Contract No. FA8903-10-C-8100. Prepared for: High Concentration Anaerobic Bioreactor (HCAB) Field Pilot Study and Pre-Processing Program Development. Eglin Air Force Base, Florida.

Baker, S., and B. Vandepeer. 2004. *Deployed force waste management*. DSTO-GD-0418. Australian Government Department of Defense. Defense Science & Technology Organization. Fairbaim, Canberra, Australia.

Bernstad, A., and J. la Cour Jansen. 2012. Separate collection of household food waste for anaerobic degradation – Comparison of different techniques from a systems perspective. *Waste Management* 32(5):806-15.

Berton, B. 2013. How Fort Collins created America's first zero-energy district. *The Atlantic Cities*. Available On Line: http://www.theatlanticcities.com/jobs-and-economy/2013/02/how-fort-collins-created-americas-first-zero-energy-district/4773/

Bisio, A. (ed). 1995. Aircraft Fuels. *Energy, technology and the environment*. Hoboken, NJ: John Wiley and Sons, Inc.

Boopathy, R. 2003. Use of anaerobic soil slurry reactors for the removal of petroleum hydrocarbons in soil. *International Biodeterioration & Biodegradation* 52(3): 161-166.

Boopathy, R. 2004. Anaerobic biodegradation of no. 2 diesel fuel in soil: A soil column study. *Bioresource Technology* 94(2): 143-151.

Bowden, J.N., S.R. Westbrook, and M.E. LePera. 1988. A Survey of JP-8 and JP-5 Properties. Interim Report. BFLRF No. 253. Ft. Belvoir, VA: Belvoir Fuels and Lubricants Research Facility. Available on-line at: http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA207721.

Browne, J. D., J.D. Murphy. 2013. Assessment of the resource associated with biomethane from food waste. *Applied Energy* 104:170-177.

Clesceri, L.S., A.E. Greenberg, and A.D. Eaton. 1998. *Standard methods for the examination of water and wastewater, 20th Ed*. Washington, DC : American Public Health Association, American Water Works Association, Water Environment Federation.

Coates, J., J. Woodward, J. Allen, P. Philp, and D. Lovley, 1997. Anaerobic degradation of polycyclic aromatic hydrocarbons and alkanes in petroleum-contaminated marine harbor sediments. *Applied and Environmental Microbiology* 63(9): 3589-3593.

Cockrell, P. 2008. Greasing digester-gas production. *Water Environment Technology* 20: 70–73.

Dai, X., N. Duan, B. Dong, and L. Dai. 2013. High-Solids Anaerobic Co-Digestion of Sewage Sludge and Food Waste in Comparison with Mono Digestions: Stability and Performance. *Waste Management* 33(2): 308-316.

Eady, D.S., S.B. Siegel, K.K. Stroup, T.M. Tomilson, H.A. Kaltenhauser, M.H. Rivera-Ramirez. 2006. *Sustain the mission project: Resource costing and cost-benefit analysis*. Arlington VA: Army Environmental Policy Institute (AEPI).

El-Mashad, H.M., R. Zhang, and J.P. Greene. 2012. Anaerobic biodegradability of selected biodegradable plastics and biobased products. *Journal of Environmental Science and Engineering* 1:108-114.

Energy Working Group (EWG). 2012. *Energy working group report to the Quadrilateral Logistics Forum*. Canberra Area, Australia. Andrew Gillespe (Chair). Director Strategic Logistics at ADF Federal Government.

Garcia-Pena, E.I., P. Parameswaran, D.W. Kang, M. Canul-Chan, R. Krajmalnik-Brown. 2011. Anaerobic digestion and co-digestion of vegetable and fruit residuals: process and microbial activity. *Bioresource Technology* 102:9447-9455.

Gekas, K. 2009. Anaerobic treatment, fuel cell at brewery. *BioCycle* 50:42. Available on-line: http://www.biocycle.net/2009/01/anaerobic-treatment-fuel-cell-at-brewery/.

Gerdes, G.L., and A.L. Jantzer. 2006. *Base camp solid waste characterization study*. ERDC/CERL TR-08-11. Champaign, IL: US Army Engineer Research and Development Center.

Goldstein, J. 2000. Anaerobic Digestion Advances. *Biocycle* 41(2): 30.

Gray, D.M.D., P. Suto, and C. Peck. 2008. *Anaerobic digestion of food waste*. Study for USEPA. No. EPA-R9-WST-06-004. East Bay Municipal Utility District.

Grishchenkov, V. G., R. T. Townsend, T. J. McDonald, R. L. Autenrieth, J. S. Bonner, and A. M. Boronin. 2000. Degradation of petroleum hydrocarbons by facultative anaerobic bacteria under aerobic and anaerobic conditions. *Process Biochemistry* 35(9): 889-896.

Hach Company. 2008. [Online] 2008. http://www.hach.com/asset-get.download.jsa?id=7639983909.

Hackmann, T.J., and J.N. Spain 2010. Ruminant ecology and evolution: Perspectives useful to ruminant livestock research and production. *Journal of Dairy Science* 93:1320-1334.

Headquarters, US Army Corps of Engineers (USACE). 2008. *Solid Waste Generation Rates at Army Base Camps*. Public Works Technical Bulletin 200-1-51. Washington DC: USACE.

_____. 2013. Base Camps. Army Techniques Publication. ATP 3-37.10. Washington, DC: USDOA.

Henze, M. 2002. Basic Biological Processes. In: Henze, M., P. Harremoes, J. la Cour Jansen, and E. Arvin. *Wastewater treatment: Biological and chemical processes. Third Edition*. Springer. p.65-129.

Ho, K-L, A.L. Pometto, A. Gadea-Rivas, J. Briceno, A. Rojas. 1999. Degradation of polylactic acid (PLA) plastic in Costa Rican soils and Iowa State University compost rows. *Journal of Environmental Polymer Degradation* 7:173-177.

Holliger, C., G. Wohlfarth, and G. Diekert. 2006. Reductive dechlorination in the energy metabolism of anaerobic bacteria. *FEMS Microbiology Reviews* 22:383-398.

Hoppenheidt, K. and J. Trankler. 1995. Biodegradable plastics and biowaste options for common treatment. *Proceedings of BIOWASTE '95 Conference. Asiborg, Denmark*.

Hunkeler, D., D. Jörger, K. Häberli, P. Höhener, and J. Zeyer. 1998. Petroleum hydrocarbon mineralization in anaerobic laboratory aquifer columns. *Journal of Contaminant Hydrology* 32:41-61.

Ike, M., D. Inoue, T. Miyano, T.T. Liu, K. Sei, S. Soda, S. Kadoshin. 2010. Microbial population dynamics during startup of a full-scale anaerobic digester treating industrial food waste in the Kyoto eco-energy project. *Bioresource Technology* 101:3952-3957.

Jones, J. (Staff Sgt). 2011. *Biogas plant nears completion, promises hope for future*. International Security Assistance Force (ISAF) News List. Available On-Line: http://www.isaf.nato.int/article/isaf-releases/biogas-plant-nears-completion-promises-hope-for-future.html

Kabouris, J.C., U. Tezel, S.G. Pavlostathis, M. Engelmann, A.C. Todd, R.A. Gillette, 2008. The anaerobic biodegradability of municipal sludge and fat, oil, and grease at mesophilic conditions. *Water Environment Research* 80: 212–221.

Kabouris, J.C., U. Tezel, S.G. Pavlostathis, M. Engelmann, J. Dulaney, R.A. Gillette, A.C. Todd. 2009. Methane recovery from the anaerobic codigestion of municipal sludge and FOG. *Bioresource Technology* 100:3701-3705.

Lansing, S., R.B. Botera, and J. Martin. 2007. Small-scale digesters in Costa Rica. *Biocycle International* February Issue: 48-51.

Lansing, S., R.B. Botero, and J.F. Martin. 2008a. Waste treatment and biogas quality in small-scale agricultural digesters. *Bioresource Technology* 99:5881-5890.

Lansing, S., J. Viquez, H. Martinez, R. Botero, J. Martin. 2008b. Quantifying electricity generation and waste transformations in a low-cost, plug-flow anaerobic system. *Ecological Engineering* 34:332-348.

Lansing, S., J.F. Martin, R.B. Botero, T.N. da Silva, and E.D. da Silva. 2010. Methane production in a low-cost, unheated, plug-flow digesters treating swine manure and used cooking grease. *Bioresource Technology* 101:4362-4370.

Lansing, S., and A.R. Moss. 2010. Small-scale anaerobic digestion: Technology and applications. *10th Annual Biocycle Conference on Renewable Energy of Organics Recycling*. Available on-line at: http://www.epa.gov/agstar/documents/meeting_120210_lansing.pdf

LaRaia, S., C. Ahn, K. Keampfee, C. Leksono, and L. Rotty. 2012. Solid Waste Characterization Study. Site Specific Report. SSR-NAVFAC ESC-EV-1210.Djibuoti City, Djibuoti: Camp Lemonaire, Naval Facilities Engineering Command (NAVFAC).

Lefler, E. 2010.*Operation enduring freedom. joint engineer operation*. Initial Impressions Report. August 2010. Ft. L. Wood, MO: US Army Directorate of Environmental Integration. Manuever Support Center of Excellence.

Li, D. 2009. Methane production by anaerobic co-digestion of food waste and waste paper. *Acta Scientiae Circumstantiae* 29(3):577-583.

Lim B.S., Kim B., and Chung I. 2012. Anaerobic treatment of food waste leachate for biogas production using a novel digestion system. *Environmental Engineering Research* 17 (1): 41-46.

Maryniak, P. 2011. Army Reservist helps Afghans fuel hopes. AZCentral.com. *The Arizona Republic*. Available on-line: http://www.azcentral.com/community/chandler/articles/2011/05/17/20110517chandler-paul-maryniak-army-afghan0518.html?nclick_check=1

McCarty, P.L., and L. Semprini 1994. Groundwater tTreatment for chlorinated solvents. In Norris, R.D. (ed) *Handbook of bioremediation*. Ada, OK: Robert S. Kerr Environmental Research Laboratory.

Medina, V.F., A. Weathersby, M. Jones, and A. Morrow. 2006. Column study simulating in situ bioremediation of perchlorate using acetate as an organic substrate. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* 10(2):102-107.

Medina, V.F., and S.A. Waisner. 2011. Military solid and hazardous wastes – assessment of issues at military facilities and base camps. In Letcher, T. and Vallero, D. *WASTE: A handbook of waste management and recycling*. Elsevier Publishers. Chapter 25. p. 358-376.

Medina, V.F., H. Smith., D. Gent, A. Morrow. 2012. *Results of a laboratory feasibility study for biological treatment of Umatilla ground water*. ERDC/EL TR-12-2. Vicksburg, MS: US Army Engineer Research & Development Center Report. Available On-line: http://el.erdc.usace.army.mil/elpubs/pdf/trel12-2.pdf

Medina, V.F., M. Wynter, S.A. Waisner, S. Cosper, G. Rodriguez. 2013. The Army Net Zero Waste Program and Its Implications for Energy. In Linkov, I. (ed). *Sustainable cities and military installations*. NATO Science for Peace and Security Series. Amsterdam, NL: IOS Press.

Morrow, A.B., V.F. Medina, and B. Extine. 2010. *Biodegradation of perchlorate in laboratory reactors under different environmental conditions*. ERDC/EL TR-10-14. Vicksburg, MS: US Army Engineer Research & Development Center Report. Available On-line: http://el.erdc.usace.army.mil/elpubs/pdf/trel10-14.pdf

Nagao, N., Tajima, N., Kawai, M., Niwa, C., Kurosawa, N., Matsuyama, T., and Toda, T. 2012. Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste. *Bioresource Technology* 118:210-218.

Noblis. 2010. Sustainable Forward Operating Bases. Prepared for the Strategic Environmental Research and Development Program (SERDP). Falls Church, VA.

Office of the Assistant Chief of Staff for Installations Management (OACSIM), Headquarters, Department of the Army. 2012. Army environmental requirements and technology assessments (AERTA).

Rittmann, B.E., and P.L. McCarty. 2001. *Environmental biotechnology: Principles and applications*. New York City, NY: McGraw Hill.

Ruppert, W.H., T.A. Bush, D.P. Verdonik, J.A. Geiman,and M.A. Harrison. 2004. *Force provider solid waste characterization study*. Natick/TR-04/017. US Army Research, Development and Engineering Command Natick Soldier Center.

Scherr, K. E., Lundaa, T., Klose, V., Bochmann, G., & Loibner, A. P. 2012. Changes in bacterial communities from anaerobic digesters during petroleum hydrocarbon degradation. *Journal of Biotechnology* 157(4), 564-572.

Sierra Nevada Brewing Co. 2012. *Biennial sustainability report*. Chico CA. Available for Download: http://www.sierranevada.com/brewery/about-us/sustainability#/water-biogas-recovery

Suto, P., D.M.D. Gray, , E. Larsen, , J. Hake, , 2006. Innovative anaerobic digestion investigation of fats, oils, and grease. In: *Proceedings of the 2006 residuals and biosolids management conference* [CD-ROM], Cincinnati, OH, March 12–14, 2006, Water Environment Federation, Alexandria, Virginia, pp. 858–879.

United Nations Environmental Program (UNEP). 2010. Assessment of energy, water, and waste reduction options for the proposed AMISOM HQ Camp in Mogadishu, Somalia and the Support Base in Mombasa, Kenya. UNEP/DFS/UNSOA Technical Report.

United States Army Engineer School (USAES). 2010. *Waste management of deployed forces – commander's handbook*. Fort Leonard Wood, MO: USAES.

United States Environmental Protection Agency (USEPA). 1994. A Plain English Guide to the EPA Part 503 Biosolids Rule. EPA/832/R-93/003. Available On-line: http://water.epa.gov/scitech/wastetech/biosolids/503pe_index.cfm

United States Army Logistics Innovation Agency (USALIA). 2013. USARCEN AOR Contingency Base Waste Stream Analysis. An Analysis of Solid Waste Streams at Five Bases in the US Army Central Area of Command. Ft. Belvoir, VA: USALIA.

Viquez, J., S. Lansing, and H. Martinez. 2008. Biocycle. Evaluating digester design for electricity generation. *BioCycle Interational* February Issue: 51-54.

Vlachopoulou, M. 2010. "The anaerobic digestion of food waste with and without sewage sludge: Achievements and the potential for the ADM1." MS Thesis. Centre for Environmental Policy. Imperial College of London.

Wilson, B., N. Williams, B. Liss, B. Wilson. 2012. A comparative assessment of commercial technologies for conversion of solid waste to energy. Coral Springs, FL: ITC Renewable, LLC.

Zhang, C., Xiao, G., Peng, L., Su, H., & Tan, T. 2013. The anaerobic co-digestion of food waste and cattle manure. *Bioresource Technology* 129:170-176.

Zhang, R., H.M. El-Mashad, K. Hartman, F. Wang, G. Liu, C. Choate, and P. Gamble. 2007. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource Technology* 98:929-935.

Appendix A: Estimated Energy Generation from Food Wastes for CBs of 250, 1500, and 5000 Men

Potential Energy Generation from Food Waste

Soldiers	kWh
1	0.25
250	62
1500	369
5000	1,231

Conversions

1,000	BTU	/	ft^3 CH_4
13,400	BTU	/	kWh

Assumptions

1.65	ft^3 CH_4	/	lb wet food waste
2.00	lbs wet food waste	/	soldier-day
25%	solids content of food waste		
87%	volatile fraction of food waste solids		

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14. ABSTRACT
A study was conducted to evaluate anaerobic digestion as a means of treating organic waste from contingency bases (CBs) and generating energy from the process through biogas. The project focused on laboratory studies to evaluate the treatment of applicable wastes and determine gas production. The study found that food waste is very effectively treated, and generates relatively large gas volumes. Methane concentrations in the gas range from 60 to 70%. Studies with latrine wastes also had high gas production, and inhibition by toilet chemicals was minimal. A pilot study was conducted at the Contingency Base Integration and Technology Evaluation Center (CBITEC) at Ft. Leonard Wood. Calculations suggest that the generated gas could offset energy use by 15 to 30%, depending on the size of the CB, and fuel cost savings (fully burdened and incorporating estimates for force protection) were estimated to be as high as $500,000 per month. Some issues were identified regarding reaction instabilities that could cause the reactors to fail. Some solutions were suggested to address these issues; one in particular uses a mix of wastes, along with food, and this mixture should improve stability and increase the utility of the process.

15. SUBJECT TERMS
Anaerobic digestion
CBs
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Biogas
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CBITEC

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